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Determination of Activated Sludge Biokinetic Constants for Chemical and Plastic Industrial Wastewaters

Oklahoma State Univ., Stillwater

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Robert S. Kerr Environmental Research Lab.
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DETERMINATION OF ACTIVATED SLUDGE BIOKINETIC CONSTANTS FOR CHEMICAL AND PLASTIC INDUSTRIAL WASTEWATERS

by

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The most widely used method of wastewater treatment is biological treatment. The The use of kinetic models to describe the behavior of a biological wastewater treatment process has become widely accepted practice. The most often used kinetic models include those developed by Eckenfeler, McKinney, Lawrence and McCarty, and Gaudy. All of these models contain kinetic constants, and the usefulness of each model is a function of the reliability of the kinetic constants. However, there has not been enough information available to establish reliable values for these kinetic constants for industrial wastewaters.

This project has determined the biokinetic constants and fate for 24 toxic organic pollutants when present in a highly biodegradable wastewater. The normal approach for determining biokinetic constants has been to plot the average values. This approach masks the actual scatter of the data. This study has produced a methodology for analysis of the test results from biological activated sludge systems for determining the biological variability inherent in these types of systems.

This study also investigated the possibility of predicting the fate and effluent concentrations of the various priority pollutants. It was found that good predictions for the priority pollutants can be made.

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FOREWORD

The Environmental Protection Agency is charged by Congress to protect the Nation's land, air and water systems. Under a mandate of national environmental laws focused on air and water quality, solid waste management and the control of toxic substances, pesticides, noise, and radiation, the Agency strives to formulate and implement actions which lead to a compatible balance between human activities and the ability of natural systems to support and nurture life. In partial response to these mandates, the Robert S. Kerr Environmental Research Laboratory, Ada, Oklahoma, is charged with the mission to manage research programs to investigate the nature, transport, fate, and management of pollutants in ground water and to develop and demonstrate technologies for treating wastewaters with soils and other natural systems for controlling pollution from irrigated crop and animal production agricultural activities; for developing and demonstrating cost-effective land treatment systems for the environmentally safe disposal of solid and hazardous wastes.

EPA, as provided for in the Clean Water Act, has the responsibility to promulgate regulations to protect streams and publicly owned treatment works. An important consideration is the economic impact that these regulations may have. This report summarizes a study of the biokinetic constants and fate for 24 toxic organic pollutants. This information will aid the Agency in its effort to compute the economic impact that a given level of effluent guidelines may have on a specified industry.

Clinton W. Hall

Clinton W. Hall
Director
Robert S. Kerr Environmental Research Laboratory

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ABSTRACT

The most widely used method of wastewater treatment is biological treatment. The use of kinetic models to describe the behavior of a biological wastewater treatment process has become widely accepted practice. The most often used kinetic models include those developed by Eckenfelder, McKinney, Lawrence and McCarty, and Gaudy. Eckenfelder (first model) and McKinney use first order kinetics for substrate removal; Lawrence and McCarty, and Gaudy use the empirical Monod kinetics for substrate removal; and Eckenfelder (second order) relates the substrate removal rate as a function of the remaining substrate concentration to the initial concentration. All of these models contain kinetic constants and the usefulness of each model is a function of the reliability of the kinetic constants. However, there has not been enough information available to establish reliable values for these kinetic constants for industrial wastewaters.

Cooperative Agreement CR 806843-01-02 has determined the biokinetic constants and fate for twenty-four toxic organic pollutants when present in a highly biodegradable wastewater. Biokinetic constants were also determined for eight groups of three chemicals. The biokinetic constants were determined based upon biochemical oxygen demand (BOD_5), total organic carbon (TOC), chemical oxygen demand (COD), and specific organic chemical. The normal approach for determining biokinetic constants has been to plot the average values. This approach masks the actual scatter of the data and provides an average value or 50 percent probable value for the biokinetic constants to be used in design. This study has produced a methodology for analysis of the test results from biological activated sludge systems for determining the biological variability inherent in these types of systems.

This study also investigated the possibility of predicting the fate and effluent concentrations of the various priority pollutants. It was found that good predictions for the priority pollutants can be made. In general, it can be predicted that nitrogen compounds, phenols, oxygenated compounds, polynuclear aromatics, and phthalates will be removed by biological degradation. Aromatics will be removed by both biological degradation and stripping, except when the Henry's Law Constant is in the 10^{-5} atm·m^3/mole range, then that chemical will be removed by biological degradation only. Halogenated hydrocarbons present a special problem. Some are removed by stripping, whereas, others are removed by combined biodegradation and stripping. No parameter, such as Henry's Law Constant or partition coefficient was found that would predict which removal mechanisms would persist. Therefore, biodegradability studies must be conducted.

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LIST OF ABBREVIATIONS AND SYMBOLS

BOD_5 -- biochemical oxygen demand
COD -- chemical oxygen demand
F -- flow rate
F/M -- food to microorganism ratio FS_i/XV
F_w -- waste sludge flow rate
K -- Lawrence and McCarty's maximum substrate utilization rate
K_B -- substrate loading at which the rate of substrate utilization is one-half the maximum rate
k_d -- maintenance energy or decay coefficient
K_e -- Eckenfelder's first order substrate removal rate constant
K_e' -- Eckenfelder's second order substrate removal rate constant
K_L -- stripping rate constant
K_m -- Mckinny's substrate removal rate
K_s -- saturation constant
MLSS -- mixed liquor suspended solids
MLVSS -- mixed liquor volatile suspended solids
S_e -- effluent substrate concentration
S_i -- influent substrate concentration
SRT -- sludge retention time, θ_c
SVI -- sludge volume index
TOC -- total organic carbon
U -- $S_i - S_e/Xt$, specific substrate utilization
U_{max} -- maximum substrate utilization rate
V -- volume
VSS -- volatile suspended solids
X -- biological solids
X_e -- effluent suspended solids
X_R -- underflow solids concentration
Y_t -- true yield

α -- recycle flow ratio
θ_c -- SRT
μ_n -- observed growth rate
μ_{max} -- maximum growth rate

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SECTION 1

INTRODUCTION

Provisions in the Clean Water Act clearly require the U.S. Environmental Protection Agency to promulgate regulations to protect streams and publicly owned treatment works and to see to it that regulatory practices are in place to protect the vast investment of public funds. This law can affect nearly all industrial manufacturing plants now discharging or planning to discharge into POTW's or a stream. An important category for which effluent guidelines are needed is waste components from chemical and plastic industries. For this category, the problem is extremely difficult because of the thousands of different chemicals produced at plants across the nation. The product lines of these plants, and thus the nature of the wastes, are not fixed and change with market needs. This industrial activity consequently produces waste waters of great and changing variety in the types of pollutants they contain. Furthermore, a significant number of the growing list of priority pollutants are appearing in various waste streams from the manufacturing of chemicals and plastics.

Because of the immensity and tremendous variety of products and process routes from production, it is logical that a computer programming procedure would be developed to handle the definition of wastewater composition as well as alternate processing routes for the treatment of wastewater. Computer programs have been developed that can combine waste load information on each product, select various product treatability routes, combine them, design and cost-out a plant's treatment system, and, finally, allocate the estimated treatment costs to the contributing product process route. However, before plant costs can be modeled, the treatment design models must be established. Design models are available but the biokinetic parameters for the chemical and plastic industries are not available. Therefore, the determination of the biokinetic parameters becomes of vital concern to the success of the cost model.

The current best-practical technology (BPT) for treatment of chemical industrial and plastic manufacturing wastes usually involves activated sludge, since biological treatment is often found to be the most cost effective in dealing with relatively low concentrations of the types of organic materials in such wastes.

Modern approaches for the design of activated sludge employ mathematical process models depicting the relationships among factors affecting the kinetics of wastewater purification. All design models require quantitative assessment of numerical values for biokinetic constants for the activated

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sludge in question. These values are in general a function of the type of carbon source comprising the carbonaceous biochemical oxygen demand. Various models are available for use in designing activated sludge processes.

The primary objective of this study was to determine the biokinetic constants needed in process modeling for predicting effluent quality and design configurations of activated sludge processes treating the waste streams from chemical and plastic manufacturing. Secondary objective was to refine the method of combining the biokinetic constants of components in a mix in order to determine the overall biokinetic constants of the mix and to establish the fate of the priority pollutants in the wastewater.

SECTION 2

CONCLUSIONS

High treatment efficiencies (in terms of biochemical oxygen demand, BOD_5; chemical oxygen demand, COD; and total organic carbon, TOC) can be achieved by biological treatment of wastewaters containing toxic priority pollutants. This study has shown that priority pollutants can be accommodated in biological wastewater treatment processes. In addition, it was found that many of the priority pollutants were biodegraded to very low concentrations. In other cases, the priority pollutants were stripped to low levels without interfering with the biodegradation of the other organics.

The biokinetic constants of the wastewaters containing the priority pollutants are representative of a readily biodegradable wastewater. The biokinetic constants are subject to variability, and a frequency analysis should be used in determining the biokinetic constants. A new design model provides an alternative method for accounting for the variability of the system. This new model provides designs comparable with the other design models without the variability of the biokinetic constants.

The fate and effluent concentrations of priority pollutants can be predicted with a high degree of accuracy. Parameters such as Henry's Law Constant and Log partition coefficient are key elements in predicting the fate of priority pollutants. Some priority pollutants are both biodegraded and stripped. These are more difficult to predict. Some means of estimating the biodegradability of priority pollutants is needed.

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SECTION 3

RECOMMENDATIONS

This study has investigated the biological treatment of twenty-four toxic organic chemicals. The study also included eight groups of three chemicals as a mixture. It is recommended that additional research be conducted using chemicals that would enhance sorption as a removal mechanism. Biodegradability and fate of additional chemicals could allow the creation of a structure/activity correlation for predicting the degradability and fate of toxic organics. Cost impacts for the correction of existing problems and the ability to anticipate adverse environmental impacts from the manufacture of chemicals would be made available through the use of such correlation.

It would also be of benefit to investigate the effects of factors other than the priority pollutants. Surface tension, sulfur compounds, inorganics, etc. may be much more detrimental to biological treatment than, so called, toxic organic chemicals.

It is recommended that the water pollution control field recognize that "toxic" organic chemicals can be treated in a biological wastewater treatment plant with no detrimental effects to the treatment process.

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SECTION 4

MATERIALS AND METHODS

GENERAL EXPERIMENTAL PLAN

Continuous flow, internal recycle activated sludge pilot plants were used to develop the data needed for determining biokinetic constants. Three specific chemicals were studied each quarter. Activated sludge for starting the pilot plants was obtained from either the Ponca City, Oklahoma wastewater treatment plant or the Southside wastewater treatment plant, Tulsa, Oklahoma. The pilot plants were acclimated to the synthetic wastewater for four weeks and then sampled for two months. Fourteen pilot plants were operated to provide three SRT's for each specific chemical, three SRT's for the three chemicals combined in one wastewater, and two SRT control pilot plants.

The pilot plants were sealed reactors which made the measurement of the off-gases possible. Thus, the experimental procedures allowed for the determination of the fate of the specific chemicals.

DESCRIPTION AND OPERATION OF PILOT PLANTS

A schematic of the bench-scale activated sludge pilot plants is shown in Figure 1. These systems consisted of stainless steel internal recycle reactors with 3.0 liter activated sludge reactor volumes and 3.23 liter settling compartment volumes. The reactor and settling compartment were both fitted with air tight stainless steel covers to facilitate off-gas analysis. The wastewaters were pumped from sealed feed tanks to the reactors, and the effluents flowed by gravity from the settling compartments to collection tanks. All parts of the experimental system were constructed of materials to minimize contamination.

The influent wastewater flow rates were regulated to provide hydraulic retention times of 8 hours in the activated sludge reactors. The influent air and off-gas were measured and controlled with air flow meters. The off-gas was pulled by vacuum pumps through purge traps containing 6 inches of Tenax and 4 inches of silica gel for gas chromatograph analysis.

The following procedure was used for daily operation of the internal recycle pilot plants.

1. The feed pump was set at a flow rate to provide a hydraulic detention time of eight hours.

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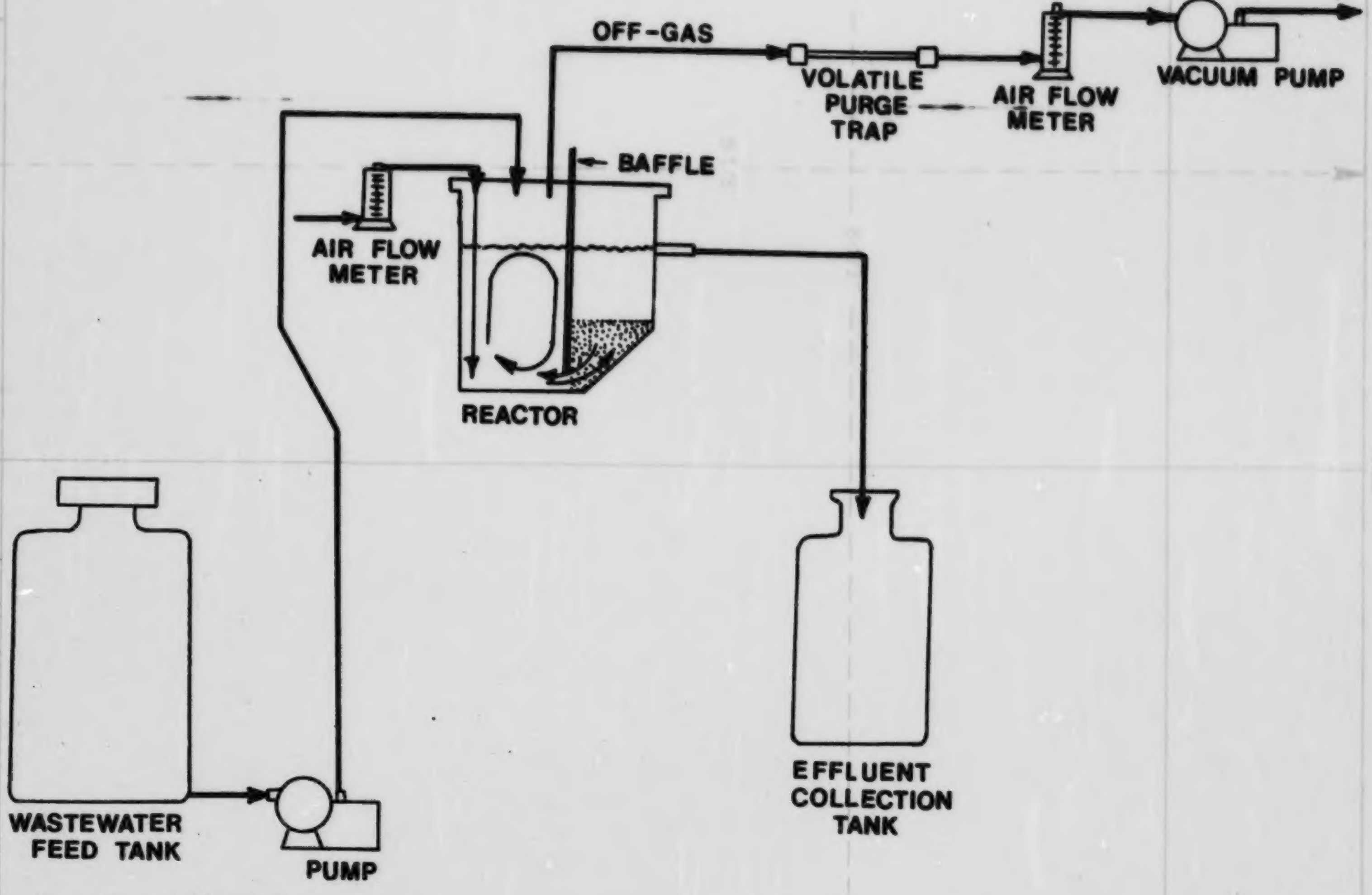
OFF-GAS
VOLATILE PURGE TRAP
AIR FLOW METER
VACUUM PUMP
BAFFLE
AIR FLOW METER
REACTOR
WASTEWATER FEED TANK
PUMP
EFFLUENT COLLECTION TANK

Figure 1. Bench-scale activated sludge pilot plants.

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2. The adjustable baffle was set at a level that provided good return flow of the return solids. This means adjusting the baffle several times per day.

3. MLVSS were wasted once each day to provide desired SRT. This was accomplished by the following procedure:

   a. A sample was collected from the aeration chamber for MLVSS analysis.

   b. The clarified effluent collection tank was mixed and a sample taken for VSS analysis.

   c. The sludge waste flow rate was calculated by

$$F_w = \frac{\frac{VX}{SRT} - FX_e}{X - X_e}$$

   where:

   F_w = waste sludge flow rate, 1/day
   SRT = sludge age, days
   V = volume of reactor, liters
   F = influent flow rate 1/day
   X_e = effluent volatile suspended solids, mg/ℓ
   X = MLVSS, mg/ℓ

   d. The baffle was pulled and the aeration chamber and clarifier were allowed to mix.

   e. A volume equal to the calculated F_w was withdrawn from the entire volume and wasted.

   f. The baffle was reset.

The municipal activated sludge was allowed to acclimate to the "base mix" wastewater for one week and then the organic compound was added to the wastewater. The organic compound was first added at a low concentration. This concentration was increased slightly each two or three days until the desired concentration was reached. This build-up period took from two to three weeks. Three pilot plants were operated for each compound - each at a different SRT. The SRT's were selected so that there would be a spread in the effluent BOD_5 achieved by the three pilot plants.

During each quarter the pilot plants were operated as:

Set No.	Number of Pilot Plants	Feed	Remarks
1	2	Base mix	Two sludge ages
2	3	BM*+ compound A	Three sludge ages
3	3	BM + compound B	Three sludge ages
4	3	BM + compound C	Three sludge ages
5	3	BM + compounds A, B, C	Three sludge ages

* BM = base mix

A total of fourteen pilot plants were operated at a time. The concentration of compounds A, B, and C in the combined units was one-third of the concentration of those compounds in the other units.

The synthetic wastewater included selected organic chemicals combined with a "base mix". The "base mix" was a readily biodegradable substrate which consisted of:

ethylene glycol	1 volume
ethyl alcohol	1 volume
acetic acid	1 volume
glutamic acid	1 weight
glucose	1 weight
phenol	0.2 weight
ammonium sulfate	1.8 weight
phosphoric acid	0.14 volume
magnesium sulfate	0.7 weight
manganese sulfate	0.07 weight
calcium chloride	0.07 weight
ferric chloride	0.004 weight

Note: use of 1 gm of weight equivalent to 1 mℓ of volume

The "base mix" and organic chemicals studied were proportioned so that the BOD_5 of the wastewater was approximately 250 mg/ℓ. Table 1 gives the names of the 24 chemicals studied and the percent COD of the wastewater due to the chemicals and the "base mix". Table 2 provides the average influent BOD_5, TOC, and COD concentrations for the various wastewaters. Table 3 gives some chemical characteristics for the 24 organic chemicals. Twenty three of the chemicals are listed as priority pollutants.

In addition to the activated sludge studies, the reactors were used to determine the stripping characteristics of a specific chemical in the abscence of biological activity. During these studies, the reactor and settling compartment were initially filled with distilled water. The wastewater was then pumped from the feed tank to the reactor, and the level of TOC and specific organic compound present in the reactor was observed as a function of time. After the wastewater had been completely diluted-in; influent, effluent and off-gas samples were collected and analyzed for the specific compound under investigation.

SAMPLE SCHEDULE

The following sample schedule was followed:

Parameter	Frequency
Influent	
Flow rate	Several times per day
BOD_5	3 per week
TOC	3 per week
COD	1 per week

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TABLE 1. RELATIONSHIP BETWEEN "BASE MIX" AND POLLUTANTS IN FEED

Compound	Percent FEED COD due to Chemical	Base mix
Tetrachloroethane	9	91
Nitrobenzene	33	67
2,4 dichlorophenol	21	79
Acrylonitrile	66	34
Acrolein	66	34
1,2 dichloropropane	2	98
Benzene	67	33
Methylene chloride	5	95
Ethyl acetate	67	33
1,2 dichlorobenzene	33	67
1,2 dichloroethane	13	87
Phenol	85	15
2,4 dinitrophenol	18	82
1,3 dichlorobenzene	21	79
1,1,1 trichloroethane	16	84
Pentachlorophenol	2	98
Trichloroethylene	10	90
Bis (2-ethylhexyl) phthalate	0.2	99.8
Toluene	36	64
Ethylbenzene	18	82
Phenanthrene	0.3	99.7
Chloroform	3	97
Carbon tetrachloride	1	99
Naphthalene	5	95

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TABLE 2. WASTEWATER CONCENTRATIONS

Group	Chemical	Wastewater concentrations, mg/ℓ		
		BOD_5	TOC	COD
I	Tetrachloroethane	244	224	496
	Nitrobenzene	255	253	668
	2,4 dichlorophenol	298	234	572
	Combined	314	246	574
II	Acrylonitrile	192	189	483
	Acrolein	219	190	477
	1,2 dichloropropane	247	199	480
	Combined	279	197	565
III	Benzene	212	132	441
	Methylene chloride	287	170	480
	Ethyl acetate	259	145	450
	Combined	248	133	400
IV	1,2 dichlorobenzene	162	152	416
	1,2 dichloroethane	201	187	460
	Phenol	277	163	486
	Combined	268	176	454
V	2,4 dinitrophenol	245	203	551
	1,3 dichlorobenzene	178	136	379
	1,1,1 trichloroethane	244	183	530
	Combined	227	143	429
VI	Pentachlorophenol	265	153	470
	Trichloroethylene	295	179	530
	Bis (2-ethylhexyl) phthalate	271	159	528
	Combined	270	169	574
VII	Toluene	180	129	416
	Ethylbenzene	236	143	520
	Phenanthrene	270	166	510
	Combined	217	147	470
VIII	Chloroform	240	155	363
	Carbon tetrachloride	257	162	387
	Naphthalene	219	163	390
	Combined	317	170	409
Control	"Base Mix"	266	170	460

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TABLE 3. CHEMICAL CHARACTERISTICS

Chemical	Henry's Law Constant atm.m^3/mole	Molecular Weight	log Pow	Solubility mg/ℓ	mg/mg chemical BOD$_5$	TOC	COD
Nitrogen compounds							
Acrylonitrile	6.3×10^{-5}	53.1	-0.14	73500	0.30	0.68	2.26
Phenols							
Phenol	1.3×10^{-6}	94.1	1.46	93000	1.75	0.78	2.38
2,4 dinitrophenol	N.A.	184.1	7.53	5600	0.60	0.39	1.10
2,4 dichlorophenol	4.2×10^{-5}	163.0	2.75	4500	-	0.44	1.18
Pentachlorophenol	2.1×10^{-6}	131.4	5.01	1100	-	0.11	0.24
Aromatics							
1,2 dichlorobenzene	1.9×10^{-3}	147.0	3.38	145	-	0.49	0.90
1,3 dichlorobenzene	2.6×10^{-3}	147.0	3.38	123	-	0.38	0.35
Nitrobenzene	2.4×10^{-5}	123.1	1.86	1900	-	0.58	1.43
Benzene	6.0×10^{-3}	78.1	2.04	1700	0.55	0.92	3.08
Toluene	5.9×10^{-3}	92.1	2.69	535	1.00	0.69	2.50
Ethylbenzene	5.8×10^{-3}	106.2	3.15	206	0.73	0.50	1.60
Halogenated Hydrocarbons							
Methylene chloride	3.2×10^{-3}	84.9	1.25	16700	-	0.14	0.56
1,2 dichloroethane	1.1×10^{-3}	99.0	1.48	8300	0	0.24	0.97
1,1,1 trichloroethane	4.9×10^{-3}	187.4	2.17	950	0	0.12	0.28
1,1,2,2 tetrachloroethane	4.2×10^{-4}	167.9	2.56	2900	0	0.14	0.48
1,2 dichloropropane	2.8×10^{-3}	113.0	2.28	2700	0	0.32	1.27
Trichloroethylene	1.2×10^{-3}	266.3	2.27	1100	0	0.10	0.28
Chloroform	3.4×10^{-3}	119.2	1.97	9600	0.06	0.10	0.13
Carbon tetrachloride	3.0×10^{-2}	153.8	2.69	800	-	0.08	0.21
Oxygenated Compounds							
Acrolein	9.7×10^{-5}	56.1	-0.09	400	0.45	0.64	2.00
Polynuclear Aromatics							
Phenanthrene	1.3×10^{-4}	178.2	4.46	1.29	-	0.94	2.82
Naphthalene	1.2×10^{-3}	128.2	3.37	34.4	-	0.94	2.99
Phthalates							
Bis (2-ethylhexyl)	N.A.	391.0	8.73	3	-	0.74	2.30
Other							
Ethyl acetate	N.A.	88.1	N.A.		0.80	0.40	1.80

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Parameter	Frequency
Influent (continued)	
pH	daily
specific chemical	2 per week
Effluent	
BOD_5	3 per week
TOC	3 per week
COD	1 per week
Suspended solids	3 per week
VSS	3 per week
specific chemical	2 per week
Aeration Basin	
MLSS	3 per week
MLVSS	3 per week
Dissolved oxygen	daily
Dissolved oxygen uptake	3 per week
SVI	1 per week
pH	daily
off-gas	1 per week
specific compound of mixed liquor	1 per week
Temperature	daily

ANALYTICAL METHODS AND QUALITY ASSURANCE

The successful conduct of this Cooperative Agreement centered around the proper operation of the pilot plants, proper laboratory procedures, and the correct interpretation of the data. Therefore, a quality assurance plan was developed to accomplish the goals of the project.

Management

The project director and co-principal investigator maintained complete control of the project. They inspected the pilot plants at least two times each day. Some days the inspection visits were as many as four or five. These inspections ensured that the pilot plants were being operated in a proper manner. Such items as wastewater feed rates, air flow rates, baffle settings, and MLSS conditions were checked. Proper laboratory procedures were also routinely checked.

The project director and the co-principal investigator routinely checked all instruments and performed most routine maintenance of the laboratory instruments. They also provided unknown and spiked samples for analyses. All data analyses were conducted by these two.

Once a week a meeting of all personnel was held. A review of the week's activities was conducted. All problems encountered during the week were

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discussed by the group. This allowed all personnel to be aware of all problems encountered. Plans for the coming week were also outlined during this meeting.

Quality Assurance of Pilot Plant Operation

The key factors in the proper operation of the pilot plants include:

1. Cleaning of wastewater feed tank and feed lines.
2. Making up synthetic wastewater feed.
3. Adjustment of baffle.
4. Pump flow rates.
5. Air flow rates.

To ensure that biological growth did not develop in the wastewater feed tank or lines, a disinfection program was developed. This includes acid washing of the feed tank each time fresh synthetic wastewater was made up and the chlorination of each feed line every fourth day. After the disinfection operation, the feed tank and lines were thoroughly rinsed with tap water before being put back into operation.

It was important that the synthetic wastewater have the proper ingredients. To ensure this, TOC, COD, and BOD_5 were routinely conducted on the synthetic wastewater. Also, gas chromatography analyses were made to measure the concentration of the specific organic compound under study. The quality assurance plan for each of these tests will be discussed later.

Proper adjustment of the baffle of each pilot plant is a matter of experience. Also, either the project director or co-principal investigator checked the flow rates daily. The flow rate was checked by the volume-time method.

Laboratory Procedures

Quality assurance in the laboratory involves reagents, glassware, instruments, and analytical techniques. The laboratory analyses conducted for this project include:

1. BOD_5 - 5 day biochemical oxygen demand
2. TOC - total organic carbon
3. COD - chemical oxygen demand
4. Suspended solids
5. Volatile suspended solids
6. D.O. - dissolved oxygen
7. pH
8. Gas chromatography analysis

Sample Preservation:

Analysis was conducted immediately for most tests. However, there were times that this was not possible. For those instances the samples were filtered and stored at $4^{o}C$.

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Analytical Methods

The following analytical methods were used:

Parameter	Method
BOD_5	EPA and/or Standard Methods used. Dissolved oxygen measured by Probe method. Both total and soluble BOD_5 were determined. Soluble is defined as that left after filtering with a glass fiber filter.
TOC	Beckman 915 TOC Analyzer and Oceanography 05248 used. Only soluble TOC was determined.
COD	EPA and/or Standard Methods used.
Suspended Solids	EPA and/or Standard Methods used. Reeve angel type 934-AH glass fiber filter used
Volatilive Solids	EPA and/or Standard Methods used.
Dissolved Oxygen	Probe method
pH	Instrument
Specific Organic Compound	Analyses followed the instructions for gas chromatograph analysis given in the Federal Register, Volume 44, Number 233, December 4, 1979. F & M Model 810 GC with Tekmar LC-Purge and Trap and HP 3380 Integrator. HP 7626A GC with HP 3380 Integrator. The columns and operating conditions are given in Table 4. Percent recoveries are given in Table 5.

Glassware

Standard Kimax or Pyrex brand glassware was used in this study. All glassware was chromic acid washed before use.

Instruments

An analytical laboratory depends very heavily upon instrumentation. It was very important that these instruments be maintained in proper working conditions. The discussion below illustrates how this project ensured that these instruments were working properly.

1. Analytical Balance The analytical balance was mounted on a heavy shock-proof table and was checked and adjusted yearly by a company serviceman. Accuracy of balance was routinely checked by using known weights.

2. pH Meters The pH meters used for this project were standardized daily by using standard buffer solutions.

TABLE 4. GAS CHROMATOGRAPHY OPERATING CONDITIONS

Analysis	Conditions
Volatile Organics	Sample extraction: purge with N_2 at 40 mℓ/min for 12 minutes
	Trap: 12" x 1/8" metal tubing containing 6" Tenax and 4" silica gel
	Column: Carbopack c/0.2% Carbowax 1500 80/100 mesh
	Detector: FID
	Carrier: N_2 gas at 30 mℓ/min
	Temperature: Injector 180°C Detector: 200°C Oven: 2 min.70°C, 8°/min to 160°C, hold 5 min.
Acid Extractables	Sample extraction for wastewaters performed according to EPA procedure. Sludges were continuously extracted for 24 hours
	Column: 1% SP-1240-DA on 100/120 Supelcoport
	Detector: FID
	Carrier: N_2 gas at 30 mℓ/min
	Temperature: Injector 180°C Detector: 200°C Oven: 4 minutes at 70°C then 10°/min to 175°C hold 5 minutes
Base-Neutral Extractables	Sample extraction for wastewaters performed according to EPA procedures. Sludges were continuously extracted for 24 hours
	Column: 1% SP-2250 on 100/120 Supelcoport
	Detector: FID
	Carrier: N_2 gas at 30 mℓ/min
	Temperature: Injector: 280°C Detector: 290°C Oven: 4 minutes at 70° then 10°/min to 275° hold 5 minutes

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TABLE 5. GAS CHROMATOGRAPHY RECOVERIES FOR SPECIFIC CHEMICALS

Column	Chemicals Analyzed	Percent Recovery Wastewater	Sludge
Carbopack C/0.2% Carbowax 1500 80/100 mesh	Tetrachloroethane	100	100
	Acrylonitrile	100	100
	Acrolein	98	98
	1,2 dichloropropane	91	91
	Benzene	100	100
	Methylene chloride	100	100
	Ethyl acetate		
	1,2 dichloroethane		
	1,1,1 trichloroethane		
	Trichloroethylene	94	94
	Toluene	100	100
	Ethyl benzene	94	94
	Chloroform	100	100
	Carbon tetrachloride	100	100
1% SP-2250 on 100/120 Supelcoport	Nitrobenzene	50	
	1,2 dichlorobenzene	-	-
	1,3 dichlorobenzene	-	-
	Bis(2-ethylhexyl) phthalate	70	85
	Phenanthrene	85	
	Naphthalene	50	50
1% SP-1240-DA on 100/120 Supelcoport	2,4 dichlorophenol	75	
	Phenol		
	2,4 dinitrophenol	89	
	Pentachlorophenol	72	26

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3. Beckman 915 TOC Analyzer The Beckman 915 TOC analyzer requires good maintenance and operation practices to ensure continuous operation. The following maintenance was performed once per month:

a) repack combusion tube

b) clean and dry microfilter

c) clean and dry infrared cell

For improved operation, the instrument remained on continuously and was preconditioned with repeated injections of distilled water to obtain stable operating conditions before actual sample injection.

4. Oceanographic Total Carbon Analyzer The main concern with this instrument was to ensure there were no leaks in the system and that the drying tubes were replaced regularly with granular magnesium perchlorate.

5. Dissolved Oxygen Probe The dissolved oxygen probe was calibrated before each series of analyses.

Internal Quality Control Practices

Internal quality control practices varied for the various tests. These were:

1. BOD_5 - There are no good methods for testing the reliability of the BOD test. Our control used duplicate samples and spiked samples prepared by the project director.
2. TOC - Linearity of standards, duplicates, and recoveries from spiked solutions provided the quality assurance of the TOC analysis.
3. COD - The ferrous ammonium sulfate titrant was standardized as part of the test. Duplicates and recoveries from spiked solutions provide the quality assurance for the COD test.
4. Suspended Solids - Duplicate samples provided the only quality assurance for suspended solids.
5. GC Analysis of Specific Compounds - Quality assurance involved determining linearity of the analytical range, replicate runs, and recoveries from spiked solutions.

DETERMINATION OF BIOKINETIC CONSTANTS

The most widely used activated sludge design models include:

1. Eckenfelder
   a. First Order
   b. Second Order (Gru)
2. McKinney
3. Lawrence and McCarty
4. Gaudy

All models were developed by writing material balances describing the mass rate of change in substrate and in biomass. Eckenfelder's, McKinney's, and Lawrence and McCarty's models are obtained by writing mass balances around the entire process, whereas Gaudy's model is obtained by writing the mass balance around the bioreactor. The aeration basin design formulas obtained by each method are shown in Table 6. Table 7 shows the design formulas for steady state in S_e, X, and X_w. One major factor that is common to all the design formulas is that they contain biokinetic constants. These include:

K_e = Eckenfelder's first order substrate removal rate constant

K_e' = Eckenfelder's second order substrate removal rate constant $[S_i K_e]$

K = maximum substrate utilization rate (Lawrence and McCarty)

μ_{max} = maximum specific growth rate (Gaudy)

K_s = saturation constant (Lawrence and McCarty, Gaudy)

Y_t = true yield (all models)

K_d = maintenance energy or decay coefficient (all models)

These constants were determined by using graphical methods. These graphical methods are illustrated in Figures 2-6.

TABLE 6. AERATION BASIN DESIGN FORMULAS

Design Approach		Basic Formula	Alternate Formula
Eckenfelder	First order	$V = \frac{(S_i - S_e)\ F}{K_e\ S_e\ X}$	$V = \frac{Y_t(S_i - S_e)\ F}{\left(\frac{1}{\theta_c} + k_d\right)\ X}$
	Second order	$V = \frac{S_i(S_i - S_e)\ F}{K_e'\ S_e\ X}$	$V = \frac{Y_t\ S_i(S_i - S_e)\ F}{\left(\frac{1}{\theta_c} + k_d\right)\ X}$
McKinney		$V = \frac{(S_i - S_e)\ F}{K_m\ S_e}$	$V = \frac{Y_t(S_i - S_e)\ F}{\left(\frac{1}{\theta_c} + k_d\right)\ X}$
Lawrence and McCarty		$V = \frac{\theta_c Y_t(S_i - S_e)\ F}{\left(1 + k_d\theta_c\right)\ X}$	$V = \frac{Y_t(S_i - S_e)\ F}{\left(\frac{1}{\theta_c} + k_d\right)\ X}$
Gaudy		$V = \frac{Y_t F\left[S_i - (1 + \alpha)\ S_e\right] + \alpha X_R F}{k_d\ X} - \frac{(1 + \alpha)\ F}{k_d}$	$V = \frac{Y_t\left[S_i - (1 + \alpha)\ S_e\right]\ F}{\left(\mu_n + k_d\right)\ X}$

TABLE 7. DESIGN FORMULAS FOR STEADY STATE IN S_e, X, AND X_w

Design Approach			
Eckenfelder	$S_e = \frac{S_i - S_e}{K_e X t} = \frac{S_i}{K_e X t + 1}$	$X = \frac{Y_t (S_i - S_e)}{\left(\frac{1}{\theta_c} + k_d\right) t}$	$X_W = VX \left[\frac{Y_t (S_i - S_e)}{Xt} - k_d\right]$ $\frac{VX}{\theta_c} = VX\ \mu_n$
McKinney	$S_e = \frac{S_i}{K_m t + 1} = \frac{S_i - S_e}{K_m t}$	$X = \frac{Y_t K_m S}{\left(\frac{1}{\theta_c} + k_d\right) t} = \frac{Y_t (S_i - S_e)}{\left(\frac{1}{\theta_c} + k_d\right) t}$	$X_W = VX \left[\frac{Y_t K_m S_e}{X} - k_d\right]$ $\frac{VX}{\theta_c} = VX\ \mu_n$
Lawrence and McCarty	$S_e = \frac{K_s (1 + k_d \theta_c)}{\theta_c (Y_t K - k_d) - 1} = \frac{K_s \left(\frac{1}{\theta_c} + k_d\right)}{Y_t K - \left(\frac{1}{\theta_c} + k_d\right)}$	$X = \frac{\theta_c Y_t (S_i - S_e)}{t(1 + k_d \theta_c)} = \frac{Y_t (S_i - S_e)}{\left(\frac{1}{\theta_c} + k_d\right) t}$	$X_W = \frac{VX}{\theta_c}$
Gaudy	$S_e = \frac{K_s \left[D\left(1 + \alpha - \alpha \frac{X_R}{X}\right) + k_d\right]}{\mu_{max} - \left[D\left(1 + \alpha - \alpha \frac{X_R}{X}\right) + k_d\right]}$ $= \frac{K_s (\mu_n + k_d)}{\mu_{max} - (\mu_n + k_d)}$	$X = \frac{Y_t \left[S_i - (1 + \alpha) S_e\right] + \alpha X_R}{1 + \alpha + k_d t}$ $= \frac{Y_t \left[S_i - (1 + \alpha) S_e\right]}{(\mu_n + k_d) t}$	$X_W = VX\ \mu_n$

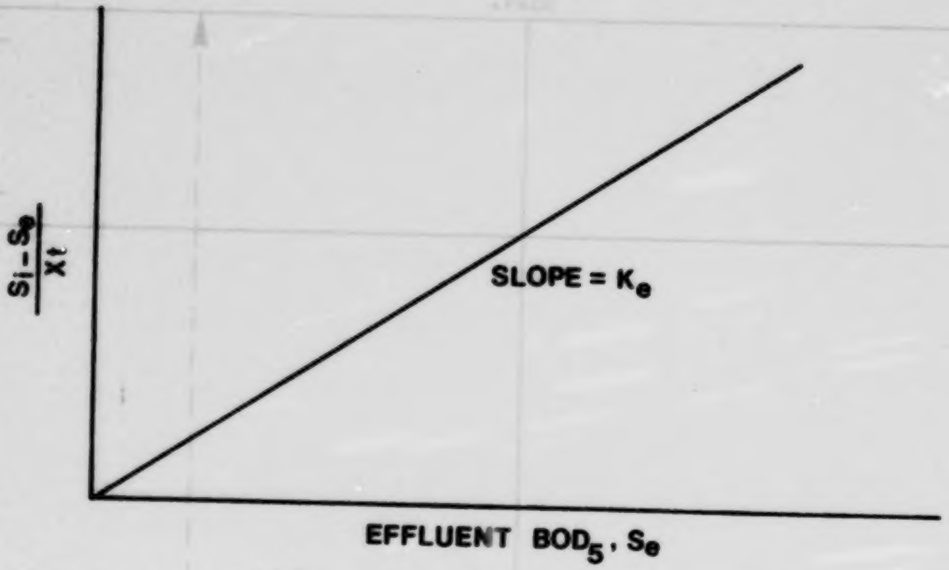

Figure 2. Graphical method for determining K_e.

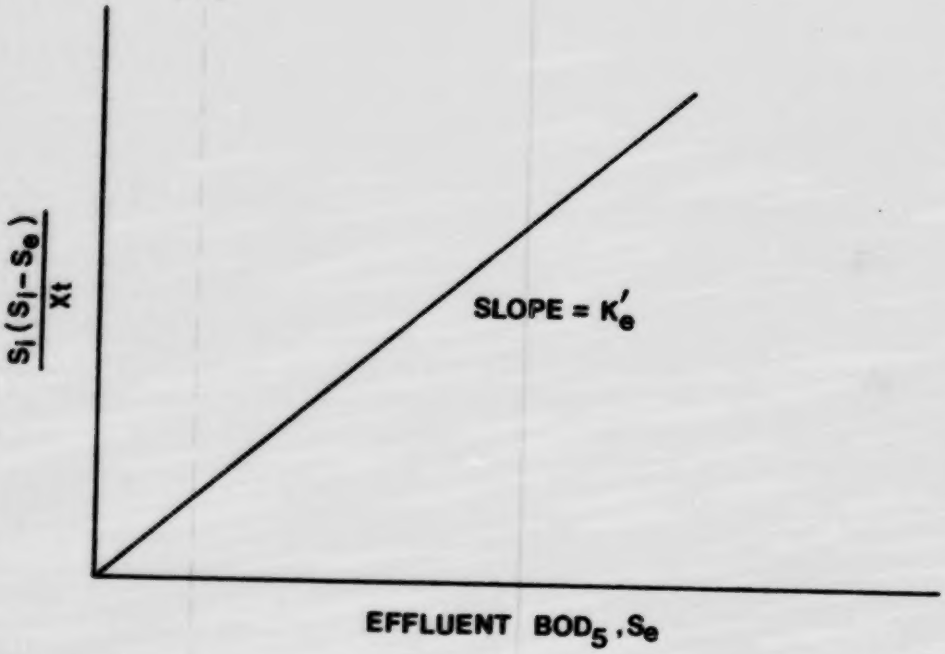

Figure 3. Graphical method for determining K_e'.

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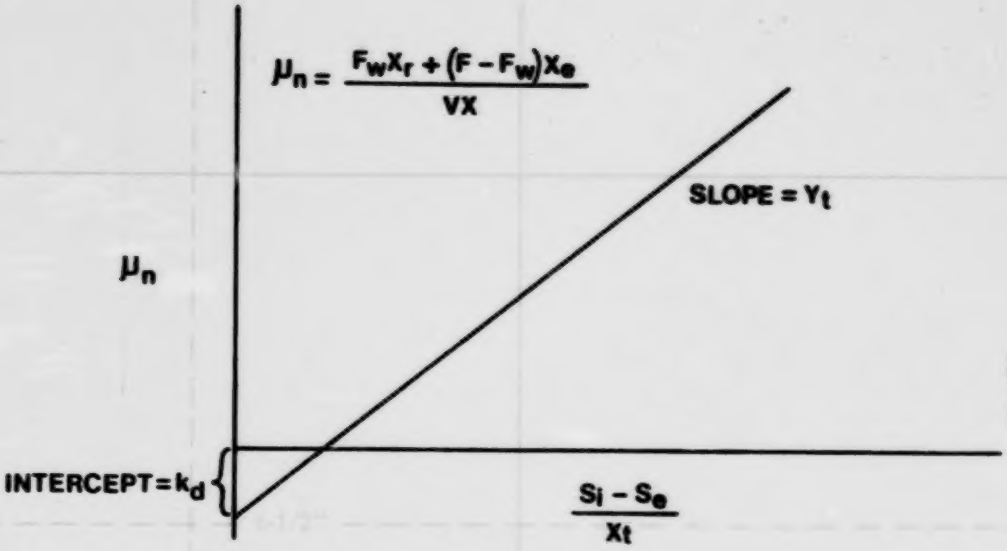

Figure 4. Graphical method for determining Y_t and K_d.

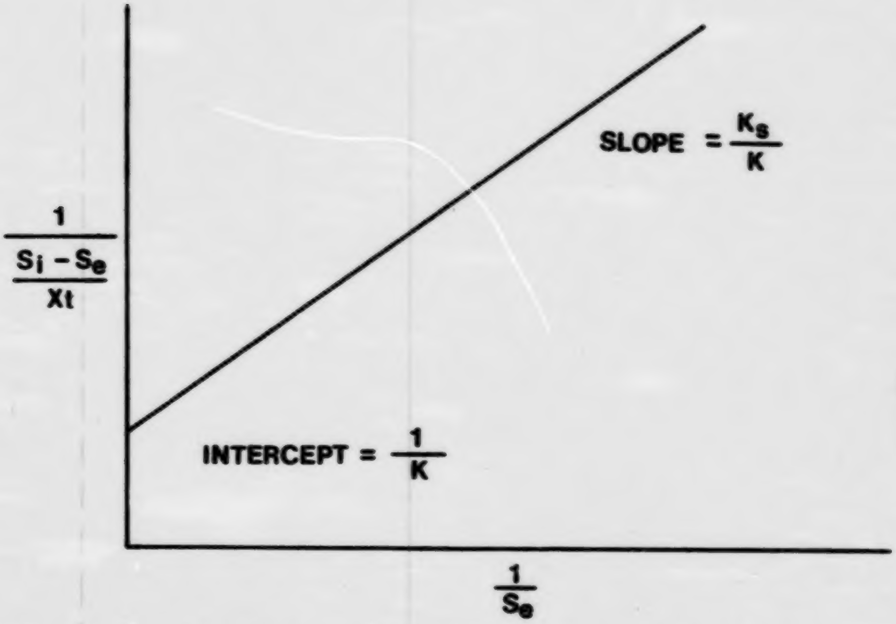

Figure 5. Graphical method for determining K and K_s.

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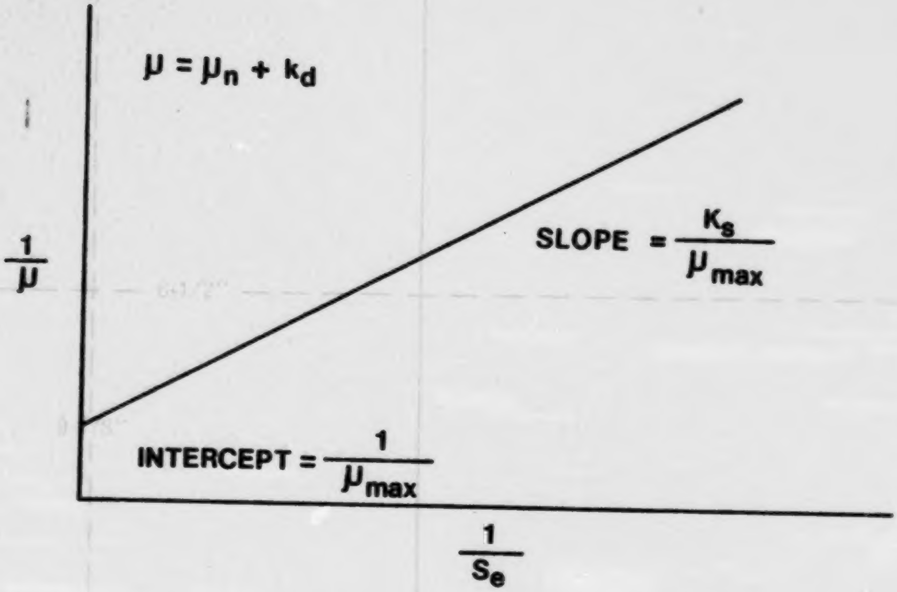

Figure 6. Graphical method for determining μ_{max} and K_s.

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SECTION 5

RESULTS

PERFORMANCE OF PILOT PLANTS

Twenty-four organic chemicals have been studied in the complete mix continuous flow bench scale activated sludge pilot plants. Figures 7-9 show typical responses to the organic chemicals. It is seen that there is a great deal of variability of the parameters with time. This is true even when the SRT is held constant. Summaries of the operating conditions and responses of the single chemical systems are shown in Table 8-13. In addition, summaries of the operating conditions and responses of the combined chemical systems are shown in Tables 14-19. The organic chemicals associated with each group were given in Table 2.

Table 8 provides the mean and standard deviation (SD) values of the sludge age, hydraulic residence time and the mixed liquor volatile solids for the single chemical systems. Table 9 gives the influent and effluent BOD$_5$ along with the F/M ratio for the single chemical systems. Tables 10 and 11 provide the influent and effluent TOC and COD along with their F/M ratios for the single chemical systems. Table 12 gives the effluent volatile solids, sludge volume index and oxygen uptake rate for the single chemical systems. Table 13 gives the influent and effluent specific chemical values with a mean F/M value for the single chemical systems. By studying the data in these tables, it can be seen that the single chemical systems performed very well during the study. High removal levels of BOD$_5$, TOC, COD, and specific chemicals were observed. In some cases the effluent suspended solids were high; however, in most cases they were at acceptable levels. Oxygen uptake rates were within acceptable levels and did not indicate any adverse effects from the wastewaters.

Table 14 provides the sludge ages, hydraulic residence times and mixed liquor volatile solids for the various combined systems. Tables 15, 16, and 17 give the influent and effluent BOD$_5$, TOC, and COD respectively. In addition, the corresponding F/M ratios are given. Table 18 provides the effluent suspended solids, sludge volume index, and oxygen uptake rate for the combined chemical systems. Table 19 gives the influent and effluent concentrations of the specific compounds for the combined chemicals. It is seen from these tables that the combined chemical systems also performed very well. No apparent adverse effects from the chemicals were observed.

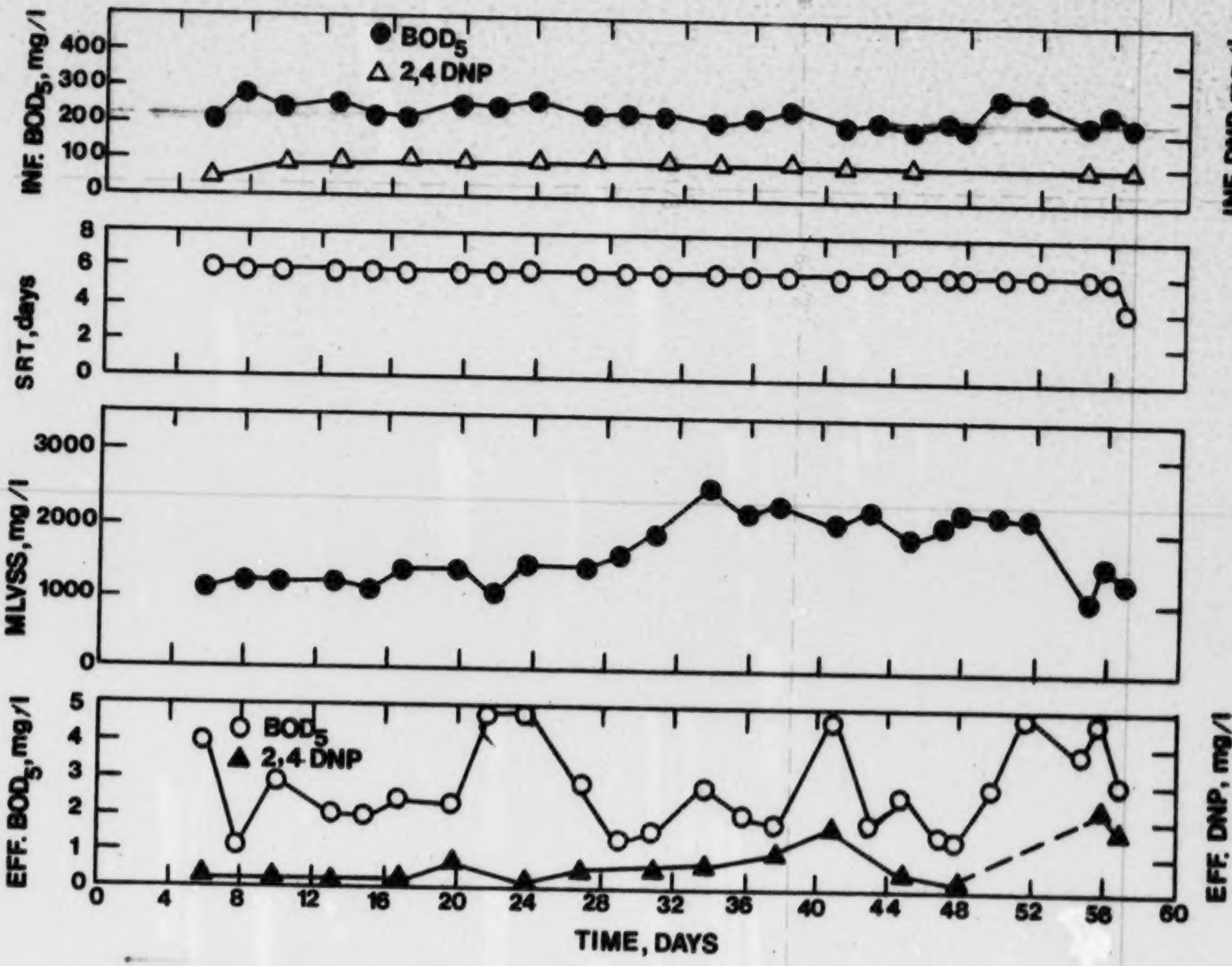

Figure 7. Response of activated sludge system receiving 2,4-dinitrophenol.

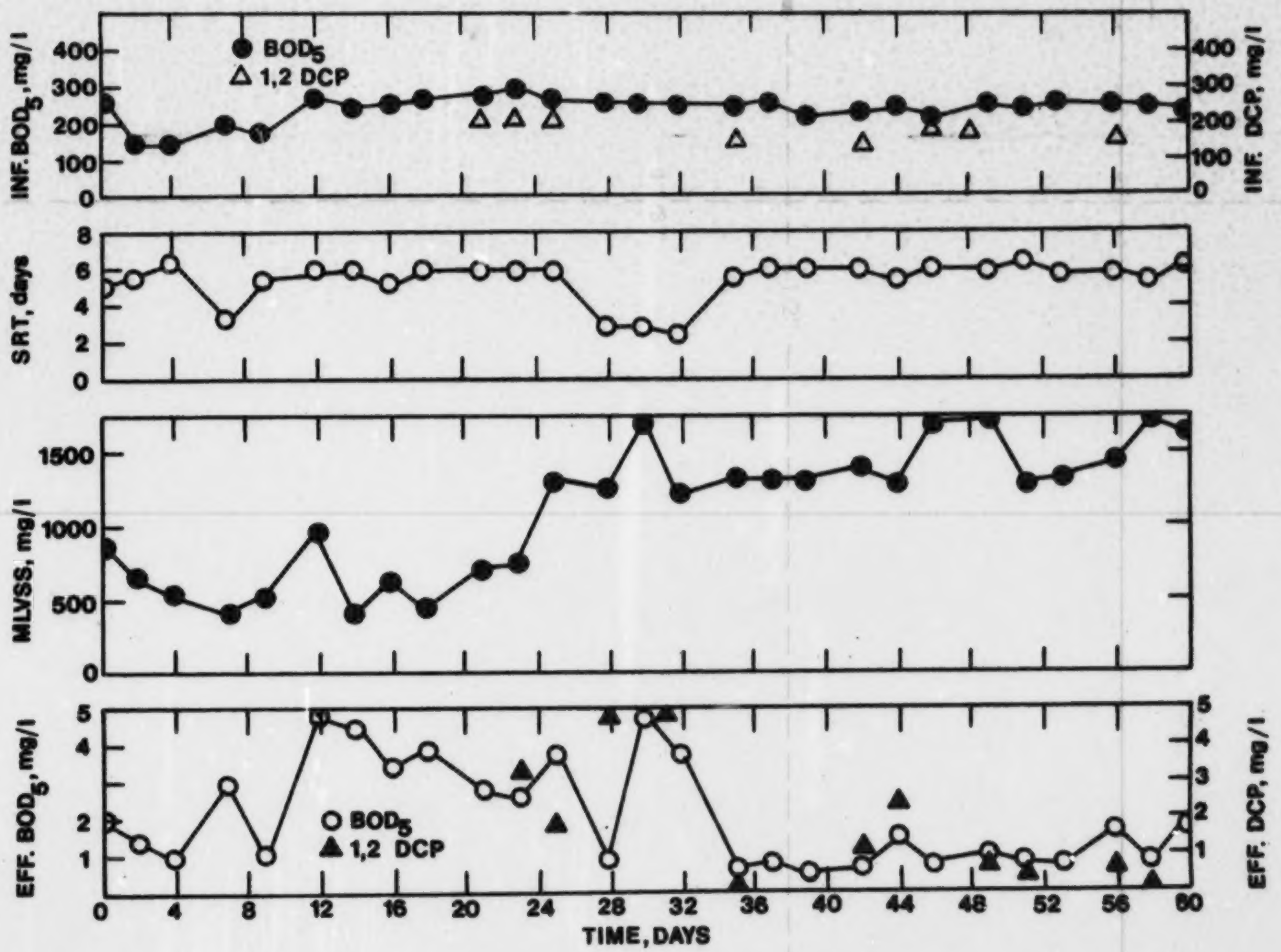

Figure 8. Response of activated sludge system receiving 1,2-dichloropropane.

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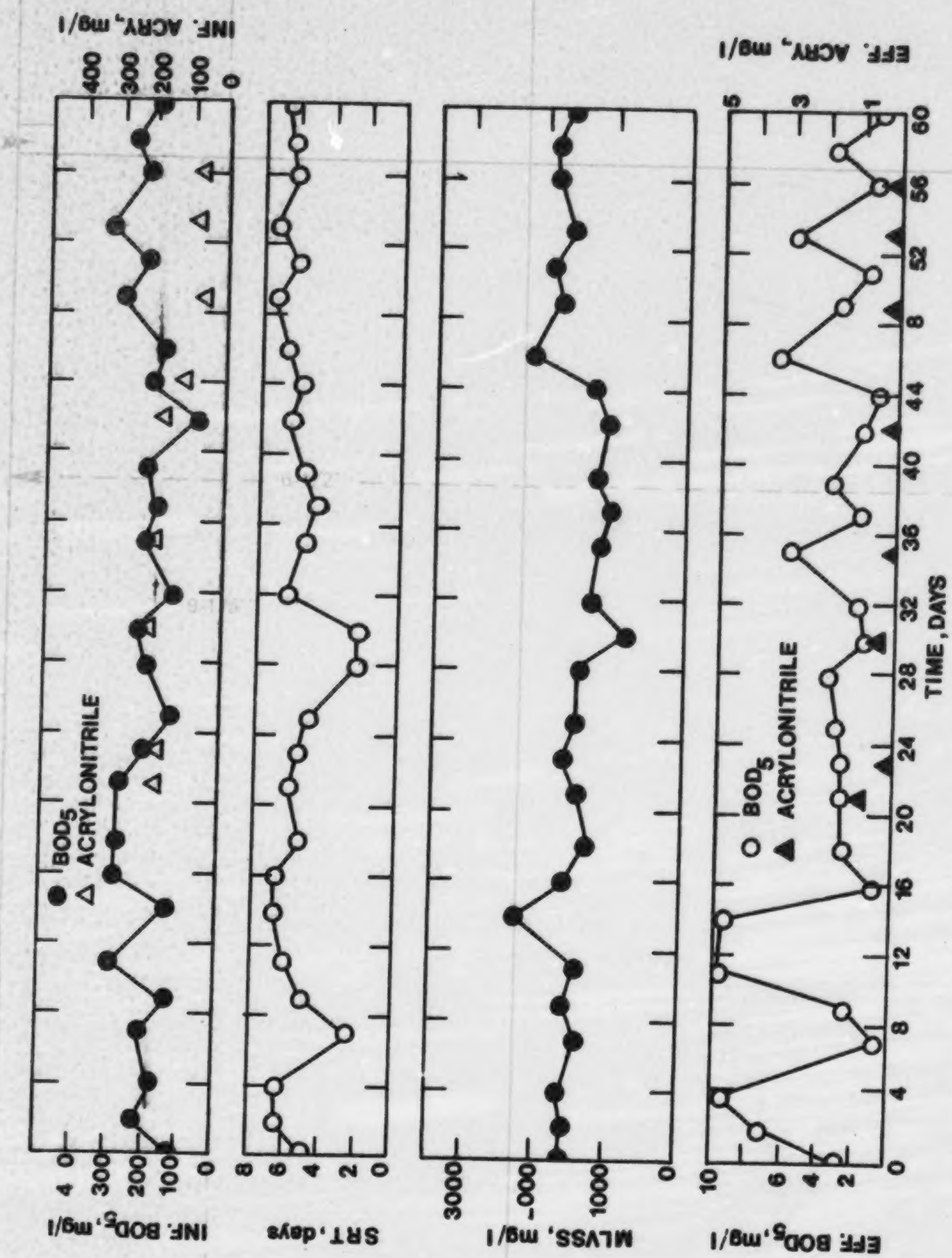

Figure 9. Response of activated sludge system receiving acrylonitrile.

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TABLE 8. SLUDGE AGE, HYDRAULIC RESIDENCE TIME, AND MIXED LIQUOR SOLIDS FOR SINGLE SYSTEMS

Compound	SRT, days		HRT,hours		MLVSS, mg/l	
	mean	S.D.	mean	S.D.	mean	S.D.
Control	2.1	0.8	8.1	0.0	732	200
	2.7	0.3	7.9	0.0	771	277
	3.8	1.0	8.1	0.0	-	-
	4.7	0.3	7.9	0.0	1090	453
	6.6	1.5	8.1	0.1	1585	454
Tetrachloroethane	1.6	0.8	8.4	0.3	614	238
	3.6	1.0	8.2	1.1	1140	401
	7.9	4.8	8.1	0.3	2338	367
Nitrobenzene	2.0	0.4	8.6	0.5	648	177
	3.7	0.4	8.0	0.5	1743	373
	7.6	0.4	8.1	0.6	2531	368
2,4-Dichlorophenol	1.8	0.2	8.1	0.0	1073	442
	3.8	0.6	8.1	0.0	1814	521
	6.1	2.0	8.2	0.0	1880	620
Acrylonitrile	1.8	0.4	8.5	0.5	666	229
	4.1	0.5	8.4	0.3	1314	163
	5.6	1.3	8.1	0.2	1539	307
Acrolein	1.8	0.3	8.5	0.6	515	183
	3.6	1.0	8.3	0.3	1283	476
	5.7	0.9	8.1	0.3	1596	400
1,2-Dichloropropane	2.0	0.6	8.8	0.4	458	167
	3.7	0.5	8.3	0.5	1024	280
	6.3	1.7	8.4	0.5	1129	462
Benzene	2.0	0.1	8.2	0.3	558	97
	4.0	0.4	8.5	0.4	861	173
	6.2	0.9	8.1	0.2	1186	161
Methylene Chloride	2.1	0.4	8.2	0.3	720	202
	4.2	0.6	8.4	0.2	984	200
	6.1	0.6	8.3	0.2	1258	383
Ethyl Acetate	2.0	0.3	8.7	0.3	617	246
	3.9	0.4	8.1	0.2	911	327
	5.8	0.6	8.5	0.5	972	317

(continued)

TABLE 8. (continued)

Compound	SRT, days mean	SRT, days S.D.	HRT, hours mean	HRT, hours S.D.	MLVSS, mg/1 mean	MLVSS, mg/1 S.D.
1,2 Dichlorobenzene	2.0	0.2	8.7	0.2	377	126
	4.0	0.2	8.2	0.2	787	236
	5.9	0.4	8.3	0.3	713	191
1,2-Dichloroethane	2.0	0.1	8.4	0.4	634	144
	4.1	0.3	8.2	0.3	1075	409
	6.0	0.6	8.1	0.3	1252	367
Phenol	2.0	0.1	8.4	0.4	661	92
	4.1	0.1	8.3	0.2	1006	177
	6.2	0.2	8.4	0.3	1108	180
2,4-Dinitrophenol	1.7	0.5	8.3	0.4	709	216
	3.7	0.9	8.2	0.2	1516	692
	5.8	0.8	8.2	0.2	1673	474
1,3-Dichlorobenzene	2.0	0.1	8.8	0.2	466	165
	3.9	0.1	8.2	0.4	802	339
	5.4	1.1	8.2	0.3	958	435
1,1,1-Trichloroethane	2.1	0.1	8.5	0.2	596	146
	4.1	0.2	8.4	0.2	1458	548
	6.0	0.5	8.1	0.3	1286	308
Pentachlorophenol	2.0	0.2	8.4	0.3	428	169
	4.0	0.1	8.2	0.2	1055	254
	6.0	0.4	8.7	0.2	1296	255
Trichloroethylene	2.0	0.0	8.3	0.3	951	149
	4.1	0.1	8.2	0.0	1415	220
	6.0	0.1	8.0	0.0	1372	153
Bis(2-ethylhexyl) phthalate	2.1	0.1	8.4	0.2	761	170
	4.0	0.1	8.1	0.1	1111	138
	6.2	0.4	8.5	0.2	1263	201
Toluene	2.0	0.0	8.4	0.3	537	103
	4.0	0.2	8.1	0.2	862	152
	6.0	0.0	8.7	0.3	1151	181
Ethylbenzene	2.0	0.1	8.1	0.1	632	178
	4.0	0.1	8.1	0.1	969	436
	5.7	1.6	8.1	0.2	970	384

(continued)

TABLE 8. (continued)

Compound	SRT, days		HRT, hours		MLVSS, mg/l	
	mean	S.D.	mean	S.D.	mean	S.D.
Phenanthrene	2.0	0.2	8.3	0.1	1127	145
	4.0	0.0	8.3	0.1	1214	148
	6.1	0.1	8.0	0.1	1324	149
Chloroform	2.0	0.0	8.3	0.4	446	107
	4.0	0.1	8.2	0.2	927	17
	6.0	0.0	8.3	0.6	1328	275
Carbon tetrachloride	2.1	0.2	8.4	0.2	715	112
	4.1	0.2	8.4	0.1	1442	500
	5.9	0.2	8.1	0.1	1459	266
Naphathalene	2.0	0.0	8.6	0.5	740	103
	4.0	0.1	8.3	0.3	1109	272
	6.0	0.0	8.7	0.5	1297	264

TABLE 9. INFLUENT AND EFFLUENT BOD_5 FOR SINGLE SYSTEMS

Compound	SRT, days		F/M		Influent BOD_5 mg/l		Effluent BOD_5 mg/l	
	mean	S.D.	mean	S.D.	mean	S.D.	mean	S.D.
Control	2.1	0.8	1.32	0.38	296	50	4.4	2.0
	2.7	0.3	1.06	0.64	226	50	4.2	1.7
	3.8	1.0	0.88	0.25	304	45	4.2	2.5
	4.7	0.3	0.76	0.33	229	37	4.8	3.1
	6.6	1.5	0.56	0.16	277	19	2.3	1.6
Tetrachloroethane	1.6	0.8	1.64	0.94	247	37	2.5	2.0
	3.6	1.0	0.81	0.49	244	40	2.0	1.3
	7.9	4.8	0.33	0.11	244	40	2.0	1.2
Nitrobenzene	2.0	0.4	1.70	1.21	254	32	3.4	1.5
	3.7	0.4	0.51	0.15	254	32	2.7	1.4
	7.6	0.4	0.37	0.10	254	32	1.8	0.9
2,4-Dichlorophenol	1.8	0.2	1.10	0.47	296	40	3.8	2.9
	3.8	0.6	0.59	0.25	298	38	3.5	3.3
	6.1	2.0	0.55	0.13	298	37	3.8	4.0
Acrylonitrile	1.8	0.4	0.92	0.46	192	77	6.6	6.2
	4.1	0.5	0.42	0.16	192	77	3.7	1.9
	5.6	1.3	0.39	0.18	192	77	4.0	2.8
Acrolein	1.8	0.3	1.38	0.53	224	43	9.9	4.3
	3.6	1.0	0.54	0.23	219	53	7.5	2.4
	5.7	0.9	0.42	0.13	219	53	5.1	1.9
1,2-Dichloropropane	2.0	0.6	1.69	0.75	247	37	2.9	1.8
	3.7	0.5	0.75	0.23	247	37	1.1	0.5
	6.3	1.7	0.76	0.38	247	37	2.1	1.6
Benzene	2.0	0.1	1.13	0.38	208	48	1.7	0.9
	4.0	0.4	0.72	0.22	212	43	1.7	1.1
	6.2	0.9	0.54	0.12	213	37	1.5	0.7
Methylene Chloride	2.1	0.4	1.25	0.35	287	32	3.1	3.6
	4.2	0.6	0.90	0.32	287	33	1.2	0.8
	6.1	0.6	0.72	0.26	281	35	2.1	1.5
Ethyl Acetate	2.0	0.3	1.27	0.44	259	59	1.6	0.9
	3.9	0.4	1.02	0.42	278	41	1.2	0.7
	5.8	0.6	0.78	0.29	247	63	1.7	0.7

(continued)

TABLE 9. (continued)

Compound	SRT, days		F/M		Influent BOD_5 mg/l		Effluent BOD_5 mg/l	
	mean	S.D.	mean	S.D.	mean	S.D.	mean	S.D.
1,2 Dichlorobenzene	2.0	0.2	1.27	0.44	162	38	3.3	1.8
	4.0	0.2	0.68	0.38	159	38	3.2	2.6
	5.9	0.4	0.71	0.28	162	39	2.6	2.1
1,2 Dichloroethane	2.0	0.1	0.95	0.33	198	41	1.2	0.7
	4.1	0.3	0.64	0.29	201	41	1.5	1.1
	6.0	0.6	0.56	0.22	212	27	1.7	0.8
Phenol	2.0	0.1	1.22	0.21	277	20	1.1	0.9
	4.1	0.1	0.83	0.19	277	20	1.3	1.5
	6.2	0.2	0.73	0.16	276	20	1.3	1.1
2,4 Dinitrophenol	1.7	0.5	1.11	0.43	242	27	3.5	1.3
	3.7	0.9	0.58	0.24	245	29	3.1	1.0
	5.8	0.8	0.48	0.14	245	29	3.1	1.7
1,3 Dichlorobenzene	2.0	0.1	1.15	0.48	180	25	2.4	1.4
	3.9	0.1	0.64	0.20	177	28	2.3	1.0
	5.4	1.1	0.64	0.30	178	30	2.1	0.9
1,1,1 Trichoroethane	2.1	0.1	1.21	0.33	244	57	2.9	1.4
	4.1	0.2	0.56	0.27	242	55	3.0	2.7
	6.0	0.5	0.58	0.18	245	57	2.0	1.4
Pentachlorophenol	2.0	0.2	2.11	1.15	267	40	6.9	4.3
	4.0	0.1	0.78	0.27	265	43	2.6	2.1
	6.0	0.4	0.57	0.13	263	43	2.5	1.2
Trichloroethylene	2.0	0.0	0.92	0.20	293	34	3.7	3.1
	4.1	0.1	0.62	0.12	295	34	2.2	1.2
	6.0	0.1	0.65	0.12	294	33	3.7	2.7
Bis (2-ethylhexyl) phthalate	2.1	0.1	1.05	0.26	271	38	1.4	0.9
	4.0	0.1	0.74	0.13	273	38	1.1	0.6
	6.2	0.4	0.62	0.13	269	35	1.9	1.8
Toluene	2.0	0.0	0.98	0.35	180	41	1.5	0.8
	4.0	0.2	0.65	0.24	180	41	1.1	0.5
	6.0	0.0	0.45	0.13	180	41	1.0	0.4
Ethylbenzene	2.0	0.1	1.15	0.41	228	37	1.5	1.0
	4.0	0.1	0.82	0.52	236	28	1.5	0.8
	5.7	1.6	0.91	0.49	233	31	1.8	1.0

(continued)

TABLE 9. (continued)

Compound	SRT, days		F/M		Influent BOD_5 mg/l		Effluent BOD_5 mg/l	
	mean	S.D.	mean	S.D.	mean	S.D.	mean	S.D.
Phenanthrene	2.0	0.2	0.71	0.14	270	33	2.1	1.9
	4.0	0.0	0.66	0.11	275	32	2.4	2.0
	6.1	0.1	0.62	0.09	269	34	2.0	1.8
Chloroform	2.0	0.0	1.63	0.39	240	27	8.5	5.0
	4.0	0.1	0.76	0.17	235	22	1.8	1.5
	6.0	0.0	0.56	0.17	241	24	2.0	1.0
Carbon Tetrachloride	2.1	0.2	1.06	0.30	257	43	6.8	5.2
	4.1	0.2	0.56	0.17	257	43	4.4	3.8
	5.9	0.2	0.54	0.13	257	43	3.1	2.4
Naphthalene	2.0	0.0	0.84	0.14	220	25	3.1	1.5
	4.0	0.1	0.61	0.22	216	22	3.6	1.5
	6.0	0.0	0.49	0.14	219	26	4.2	1.7

TABLE 10. INFLUENT AND EFFLUENT TOC FOR SINGLE SYSTEMS

Compound	SRT, days mean	SRT, days S.D.	F/M mean	F/M S.D.	Influent TOC mg/l mean	Influent TOC mg/l S.D.	Effluent TOC mg/l mean	Effluent TOC mg/l S.D.
Control	2.1	0.8	0.67	0.30	175	30	19	12
	2.7	0.3	0.71	0.45	149	34	20	9
	3.8	1.0	0.45	0.15	171	30	14	7
	4.7	0.3	0.56	0.24	150	33	16	10
	6.6	1.5	0.41	0.12	204	14	17	8
Tetrachloroethane	1.6	0.8	1.40	0.66	222	29	10	11
	3.6	1.0	0.68	0.25	224	30	10	12
	7.9	4.8	0.32	0.08	224	30	9	10
Nitrobenzene	2.0	0.4	1.42	0.79	253	41	43	19
	3.7	0.4	0.50	0.10	253	41	30	15
	7.6	0.4	0.37	0.10	253	41	26	17
2,4-Dichlorophenol	1.8	0.2	0.80	0.34	230	47	23	12
	3.8	0.6	0.48	0.25	234	50	20	11
	6.1	2.0	0.43	0.11	234	50	21	9
Acrylonitrile	1.8	0.4	0.88	0.38	189	30	25	12
	4.1	0.5	0.42	0.10	189	30	18	15
	5.6	1.3	0.38	0.13	186	33	11	10
Acrolein	1.8	0.3	1.17	0.32	190	26	28	18
	3.6	1.0	0.48	0.17	190	26	20	14
	5.7	0.9	0.38	0.12	190	26	19	15
1,2-Dichloropropane	2.0	0.6	1.21	0.41	197	38	18	9
	3.7	0.5	0.58	0.15	199	43	18	17
	6.3	1.7	0.51	0.20	200	39	24	31
Benzene	2.0	0.1	0.69	0.23	132	42	13	6
	4.0	0.4	0.44	0.15	133	43	15	8
	6.2	0.9	0.26	0.13	135	37	8	15
Methylene Chloride	2.1	0.4	0.75	0.27	170	27	18	9
	4.2	0.6	0.53	0.18	171	26	19	10
	6.1	0.6	0.43	0.18	165	31	20	11
Ethyl Acetate	2.0	0.3	0.74	0.29	145	29	13	6
	3.9	0.4	0.57	0.21	158	21	13	7
	5.8	0.6	0.45	0.15	142	28	14	11

(continued)

TABLE 10. (continued)

Compound	SRT, days		F/M		Influent TOC mg/l		Effluent TOC mg/l	
	mean	S.D.	mean	S.D.	mean	S.D.	mean	S.D.
1,2 Dichlorobenzene	2.0	0.2	1.19	0.35	152	22	20	7
	4.0	0.2	0.65	0.34	154	22	20	10
	5.9	0.4	0.67	0.21	151	23	17	10
1,2 Dichloroethane	2.0	0.1	0.84	0.26	185	19	19	6
	4.1	0.3	0.57	0.19	187	19	19	6
	6.0	0.6	0.48	0.16	184	20	18	6
Phenol	2.0	0.1	0.72	0.11	163	14	15	5
	4.1	0.1	0.48	0.11	163	14	16	7
	6.2	0.2	0.43	0.10	163	14	18	6
2,4 Dinitrophenol	1.7	0.5	0.91	0.33	203	31	15	7
	3.7	0.9	0.47	0.18	203	31	16	7
	5.8	0.8	0.39	0.12	203	31	14	5
1,3 Dichlorobenzene	2.0	0.1	0.95	0.55	136	21	7	3
	3.9	0.1	0.53	0.17	136	21	7	4
	5.4	1.1	0.49	0.21	137	21	6	3
1,1,1 Trichoroethane	2.1	0.1	0.87	0.22	183	33	16	4
	4.1	0.2	0.38	0.15	184	31	15	6
	6.0	0.5	0.44	0.10	179	34	14	4
Pentachlorophenol	2.0	0.2	1.23	0.57	153	19	15	5
	4.0	0.1	0.45	0.15	153	19	9	3
	6.0	0.4	0.34	0.08	153	20	10	4
Trichloroethylene	2.0	0.0	0.54	0.12	173	20	14	10
	4.1	0.1	0.39	0.10	179	26	9	3
	6.0	0.1	0.40	0.07	183	27	13	17
Bis (2-ethylhexyl) phthatate	2.1	0.1	0.64	0.19	157	16	8	3
	4.0	0.1	0.43	0.07	159	14	8	3
	6.2	0.4	0.38	0.08	161	12	11	5
Toluene	2.0	0.0	0.72	0.23	129	27	12	5
	4.0	0.2	0.45	0.17	129	27	13	6
	6.0	0.0	0.32	0.10	129	27	11	5
Ethylbenzene	2.0	0.1	0.76	0.26	147	25	12	4
	4.0	0.1	0.48	0.20	143	24	12	3
	5.7	1.6	0.61	0.30	149	28	14	6

(continued)

TABLE 10. (continued)

Compound	SRT, days		F/M		Influent TOC mg/l		Effluent TOC mg/l	
	mean	S.D.	mean	S.D.	mean	S.D.	mean	S.D.
Phenanthrene	2.0	0.2	0.43	0.09	165	24	18	8
	4.0	0.0	0.40	0.07	166	25	18	8
	6.1	0.1	0.37	0.06	166	26	17	8
Chloroform	2.0	0.0	1.21	0.47	158	17	25	9
	4.0	0.1	0.53	0.10	155	12	15	4
	6.0	0.0	0.37	0.10	157	20	15	3
Carbon Tetrachloride	2.1	0.2	0.62	0.19	162	24	23	11
	4.1	0.2	0.36	0.12	162	24	18	8
	5.9	0.2	0.33	0.07	160	25	17	6
Naphthalene	2.0	0.0	0.64	0.13	163	23	18	8
	4.0	0.1	0.46	0.17	163	22	21	8
	6.0	0.0	0.37	0.09	163	12	11	9

TABLE 11. INFLUENT AND EFFLUENT COD FOR SINGLE SYSTEMS

Compound	SRT, days		F/M		Influent COD mg/l		Effluent COD mg/l	
	mean	S.D.	mean	S.D.	mean	S.D.	mean	S.D.
Control	2.1	0.8	1.94	0.51	480	70	41	18
	2.7	0.3	1.99	0.93	449	26	47	15
	3.8	1.0	1.35	0.41	478	51	40	20
	4.7	0.3	1.38	0.47	462	26	41	13
	6.6	1.5	0.89	0.22	454	16	30	15
Tetrachloroethane	1.6	0.8	2.69	0.42	496	34	22	9
	3.6	1.0	1.44	0.34	496	34	22	7
	7.9	4.8	0.78	0.22	496	34	19	7
Nitrobenzene	2.0	0.4	4.18	2.25	668	72	105	15
	3.7	0.4	1.49	0.48	668	72	31	12
	7.6	0.4	0.96	0.20	668	72	29	3
2,4-Dichlorophenol	1.8	0.2	2.03	0.27	572	35	49	30
	3.8	0.6	1.02	0.23	572	35	45	31
	6.1	2.0	1.12	0.20	572	35	54	24
Acrylonitrite	1.8	0.4	3.03	1.80	483	53	59	34
	4.1	0.6	1.10	0.20	483	53	60	29
	5.6	1.3	1.09	0.30	483	53	74	45
Acrolein	1.8	0.3	2.46	0.59	477	62	117	26
	3.6	1.0	1.25	0.21	477	62	116	21
	5.7	0.9	0.92	0.25	477	62	112	14
1,2-Dichloropropane	2.0	0.6	2.97	0.78	480	69	50	29
	3.7	0.5	1.36	0.37	480	69	38	26
	6.3	1.7	1.41	0.67	480	69	43	20
Benzene	2.0	0.1	2.24	0.36	441	61	26	9
	4.0	0.4	1.49	0.36	441	61	30	14
	6.2	0.9	1.08	0.19	441	61	25	11
Methylene Chloride	2.1	0.4	2.12	0.67	477	50	23	9
	4.2	0.6	1.47	0.26	480	55	20	18
	6.1	0.6	1.42	0.52	480	55	44	19
Ethyl Acetate	2.0	0.3	2.15	0.99	450	63	26	18
	3.9	0.4	1.37	0.15	492	23	32	11
	5.8	0.6	1.42	0.63	448	74	25	16

(continued)

TABLE 11. (continued)

Compound	SRT, days		F/M		Influent COD mg/l		Effluent COD mg/l	
	mean	S.D.	mean	S.D.	mean	S.D.	mean	S.D.
1,2 Dichlorobenzene	2.0	0.2	2.93	0.81	416	41	35	18
	4.0	0.2	2.28	1.48	428	24	40	20
	5.9	0.4	1.88	0.49	416	41	49	8
1,2 Dichloroethane	2.0	0.1	2.35	0.68	515	101	34	12
	4.1	0.3	1.57	0.64	461	207	31	8
	6.0	0.6	1.09	0.27	435	21	27	11
Phenol	2.0	0.1	2.07	0.20	486	37	28	12
	4.1	0.1	1.32	0.07	486	37	26	13
	6.2	0.2	1.21	0.18	486	37	28	10
2,4 Dinitrophenol	1.7	0.5	2.63	0.81	551	54	46	10
	3.7	0.9	1.30	0.64	551	54	46	8
	5.8	0.8	1.05	0.37	551	54	47	13
1,3 Dichlorobenzene	2.0	0.1	2.52	1.28	379	30	27	18
	3.9	0.1	1.44	0.56	379	30	26	15
	5.4	1.1	1.22	0.47	379	30	29	19
1,1,1 Trichoroethane	2.1	0.1	2.58	0.78	531	67	41	9
	4.1	0.2	0.99	0.30	516	55	38	6
	6.0	0.5	1.36	0.23	532	67	36	5
Pentachlorophenol	2.0	0.2	2.79	1.76	467	53	32	13
	4.0	0.1	1.33	0.26	479	56	28	8
	6.0	0.4	1.03	0.23	474	53	25	5
Trichloroethylene	2.0	0.0	1.66	0.36	531	37	23	7
	4.1	0.1	1.24	0.33	530	35	26	10
	6.0	0.1	1.15	0.17	528	39	25	11
Bis (2-ethylhexyl) phthalate	2.1	0.1	2.20	0.73	528	86	24	4
	4.0	0.1	1.43	0.24	528	86	23	5
	6.2	0.4	1.26	0.18	499	40	25	6
Toluene	2.0	0.0	2.20	0.42	408	52	21	6
	4.0	0.2	1.59	0.36	416	54	22	14
	6.0	0.0	1.07	0.19	416	54	22	12
Ethylbenzene	2.0	0.1	2.93	0.81	517	38	35	11
	4.0	0.1	2.64	1.69	520	42	37	14
	5.7	1.6	2.26	1.24	548	32	36	10

(continued)

TABLE 11. (continued)

Compound	SRT, days mean	SRT, days S.D.	F/M mean	F/M S.D.	Influent COD mg/l mean	Influent COD mg/l S.D.	Effluent COD mg/l mean	Effluent COD mg/l S.D.
Phenanthrene	2.0	0.2	1.31	0.17	509	67	32	19
	4.0	0.0	1.22	0.17	510	72	26	19
	6.1	0.1	1.19	0.20	513	84	31	22
Chloroform	2.0	0.0	2.55	0.75	363	19	47	11
	4.0	0.1	0.86	0.52	362	18	31	10
	6.0	0.0	0.81	0.25	377	19	36	14
Carbon Tetrachloride	2.1	0.2	1.52	0.26	387	38	41	14
	4.1	0.2	0.92	0.27	387	38	34	13
	5.9	0.2	0.80	0.20	380	39	36	17
Naphthalene	2.0	0.0	1.53	0.32	386	34	35	16
	4.0	0.1	1.05	0.24	390	24	28	9
	6.0	0.0	0.83	0.19	386	34	38	15

TABLE 12. EFFLUENT SOLIDS, SLUDGE VOLUME INDEX AND OXYGEN UPTAKE RATE FOR SINGLE SYSTEMS

Compound	SRT, days		Effluent VSS, mg/l		SVI	O_2 Uptake mg/gm/hr	
	mean	S.D.	mean	S.D.	Range	mean	S.D.
Control	2.1	0.8	56	57	1080-2700	15.0	6.0
	2.7	0.3	27	39	495-2553	14.7	8.3
	3.8	1.0	33	40	595- 895	18.1	8.7
	4.7	0.3	14	15	500-1333	18.4	13.4
	6.6	1.5	49	55	436- 826	26.0	11.0
Tetrachloroethane	1.6	0.8	81	87	620-2778	23.9	9.5
	3.6	1.0	30	54	657-1250	17.8	10.3
	7.9	4.8	52	77	372- 467	9.5	5.4
Nitrobenzene	2.0	0.4	16	21	34- 350	24.3	15.0
	3.7	0.4	15	24	395- 617	19.9	14.0
	7.6	0.4	44	153	363- 466	26.2	8.6
2,4 Dichlorophenol	1.8	0.2	16	24	217- 772	67.1	35.2
	3.8	0.6	14	24	588- 783	37.1	20.9
	6.1	2.0	48	73	317- 522	33.8	22.7
Acrylonitrite	1.8	0.4	37	33	74- 545	23.2	13.3
	4.1	0.5	13	26	61- 248	14.9	4.5
	5.6	1.3	32	49	59- 126	17.1	5.7
Acrolein	1.8	0.3	24	18	21- 69	31.4	24.8
	3.6	1.0	14	16	54- 278	35.5	7.3
	5.7	0.9	11	16	80- 308	69.0	56.7
1,2 Dichloropropane	2.0	0.6	21	32	244-2600	16.4	18.0
	3.7	0.5	10	21	784-1283	17.0	8.6
	6.3	1.7	5	7	472- 795	20.2	4.4
Benzene	2.0	0.1	6	8	375-1600	23.4	10.5
	4.0	0.4	8	9	800-1000	20.2	8.5
	6.2	0.9	19	19	180-1000	19.2	6.0
Methylene Chloride	2.1	0.4	42	39	190-2100	29.1	17.9
	4.2	0.6	23	20	900-2200	27.5	16.9
	6.1	0.6	18	20	500-1200	34.5	21.9
Ethyl Acetate	2.0	0.3	18	42	230-1600	22.0	7.6
	3.9	0.4	17	17	330-3000	21.3	8.4
	5.8	0.6	21	23	530-1500	17.8	10.8

(continued)

TABLE 12. (continued)

Compound	SRT, days mean	SRT, days S.D.	Effluent VSS, mg/l mean	Effluent VSS, mg/l S.D.	SVI Range	O_2 Uptake mg/gm/hr mean	O_2 Uptake mg/gm/hr S.D.
1,2 Dichlorobenzene	2.0	0.2	19	25	191-2143	17.4	7.3
	4.0	0.2	7	8	115-1591	11.9	4.1
	5.9	0.4	18	15	52- 210	14.4	3.9
1,2 Dichloroethane	2.0	0.1	8	16	273-1485	23.4	9.7
	4.1	0.3	17	32	527-3464	21.6	14.5
	6.0	0.6	15	25	491-1234	12.9	5.6
Phenol	2.0	0.1	5	6	1156-1778	11.8	3.5
	4.1	0.1	6	9	748-1700	10.7	2.2
	6.2	0.2	7	10	621-1125	11.2	2.9
2,4 Dinitrophenol	1.7	0.5	108	139	208-1843	19.2	4.0
	3.7	0.9	90	182	96- 887	13.1	3.6
	5.8	0.8	42	64	76- 890	12.4	2.9
1,3 Dichlorobenzene	2.0	0.1	10	10	158- 911	18.6	6.4
	3.9	0.1	4	4	83-1288	19.7	5.9
	5.4	1.1	19	33	56- 520	18.3	6.6
1,1,1 Trichloroethane	2.1	0.1	2	3	61- 192	23.2	8.3
	4.1	0.2	3	5	131- 673	14.7	7.8
	6.0	0.5	6	12	350-1773	12.6	7.6
Pentachlorophenol	2.0	0.2	31	29	170-4567	18.6	3.6
	4.0	0.1	12	26	433-1242	14.2	5.3
	6.0	0.4	14	24	312- 980	13.0	3.4
Trichloroethylene	2.0	0.0	13	17	469-1428	10.6	3.3
	4.1	0.1	17	26	569- 931	9.1	3.1
	6.0	0.1	24	22	543- 840	10.0	3.2
Bis(2-ethylhexyl) phthalate	2.1	0.1	5	7	316-1572	14.0	2.5
	4.0	0.1	3	5	248- 846	12.6	1.1
	6.2	0.4	16	2	623- 897	13.5	2.4
Toluene	2.0	0.0	3	4	104- 829	15.9	6.5
	4.0	0.2	4	3	497-1059	8.8	1.7
	6.0	0.0	3	4	551- 829	7.1	2.3
Ethylbenzene	2.0	0.1	27	33	1133-4195	24.2	13.4
	4.0	0.1	34	32	675-2830	11.3	4.0
	5.7	1.6	30	37	859-5319	17.8	15.4

(continued)

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TABLE 12. (continued)

Compound	SRT, days mean	SRT, days S.D.	Effluent VSS, mg/l mean	Effluent VSS, mg/l S.D.	SVI Range	O$_2$ Uptake mg/gm/hr mean	O$_2$ Uptake mg/gm/hr S.D.
Phenanthrene	2.0	0.2	5	4	455- 931	10.3	1.2
	4.0	0.0	9	5	485- 854	9.9	1.9
	6.1	0.1	15	13	460-1086	10.2	3.2
Chloroform	2.0	0.0	20	22	58- 494	25.6	10.8
	4.0	0.1	18	33	548-1275	11.6	2.8
	6.0	0.0	7	16	149- 948	10.2	3.5
Carbon Tetrachloride	2.1	0.2	11	10	35-1961	18.4	1.5
	4.1	0.2	7	6	52-1042	15.0	1.4
	5.9	0.2	2	3	135- 513	10.5	1.8
Naphthalene	2.0	0.0	9	13	320-1309	12.4	4.4
	4.0	0.1	7	5	547-2846	16.9	11.7
	6.0	0.0	13	12	55- 595	18.1	11.6

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TABLE 13. INFLUENT AND EFFLUENT CONCENTRATIONS OF SPECIFIC COMPOUND FOR SINGLE SYSTEMS

Compound	SRT, days		F/M	Influent mg/l		Effluent µg/l	
	mean	S.D.	mean	mean	S.D.	mean	S.D.
Control	2.1	0.8					
	2.7	0.3					
	3.8	1.0					
	4.7	0.3					
	6.6	1.5					
Tetrachloroethane	1.6	0.8	0.94	201	63	13,000	7,300
	3.6	1.0	0.52	201	63	15,300	10,600
	7.9	4.8	0.25	201	63	11,100	5,100
Nitrobenzene	2.0	0.4	0.43	100	32	24,000	23,700
	3.7	0.4	0.17	100	32	3,600	2,300
	7.6	0.4	0.12	100	32	2,200	2,400
2,4-Dichlorophenol	1.8	0.2	0.21	75	--	11,600	--
	3.8	0.6	0.12	75	--	5,600	--
	6.1	2.0	0.12	75	--	3,600	--
Acrylonitrite	1.8	0.4	0.64	152	66	≤50	--
	4.1	0.5	0.33	152	66	≤50	--
	5.6	1.3	0.29	152	66	≤50	--
Acrolein	1.8	0.3	0.34	62	31	≤50	--
	3.6	1.0	0.14	62	31	≤50	--
	5.7	0.9	0.12	62	31	≤50	--
1, 2-Dichloropropane	2.0	0.6	1.08	182	52	1,950	1,670
	3.7	0.5	0.51	182	52	1,530	1,380
	6.3	1.7	0.46	182	52	1,810	1,880
Benzene	2.0	0.1	0.80	153	25	270	650
	4.0	0.4	0.50	153	25	70	60
	6.2	0.9	0.38	153	25	40	30
Methylene Chloride	2.1	0.4	0.73	180	63	860	460
	4.2	0.6	0.52	180	63	690	590
	6.1	0.6	0.41	180	63	510	800
Ethyl Acetate	2.0	0.3	0.75	167	47	500	790
	3.9	0.4	0.54	167	47	270	370
	5.8	0.6	0.49	167	47	210	730

(continued)

TABLE 13. (continued)

Compound	SRT, days mean	SRT, days S.D.	F/M mean	Influent mg/l mean	Influent mg/l S.D.	Effluent µg/l mean	Effluent µg/l S.D.
1,2 Dichlorobenzene	2.0	0.2	0.61	83	20	≤50	--
	4.0	0.2	0.31	83	20	≤50	--
	5.9	0.4	0.34	83	20	≤50	--
1,2 Dichloroethane	2.0	0.1	1.16	258	84	3,940	1,950
	4.1	0.3	0.70	258	84	3,930	2,100
	6.0	0.6	0.61	258	84	3,700	2,180
Phenol	2.0	0.1	0.75	173	11	≤10	--
	4.1	0.1	0.50	173	11	≤10	--
	6.2	0.2	0.45	173	11	≤10	--
2,4 Dinitrophenol	1.7	0.5	0.39	96	4	≤250	--
	3.7	0.9	0.19	96	4	≤250	--
	5.8	0.8	0.17	96	4	664	468
1,3 Dichlorobenzene	2.0	0.1	0.40	69	12	1,280	3,900
	3.9	0.1	0.25	69	12	810	1,840
	5.4	1.1	0.21	69	12	360	2,270
1,1,1 Trichoroethane	2.1	0.1	0.56	118	28	630	1,010
	4.1	0.2	0.23	118	28	970	1,590
	6.0	0.5	0.27	118	28	450	530
Pentachlorophenol	2.0	0.2	0.05	8	1	531	743
	4.0	0.1	0.02	8	1	190	453
	6.0	0.4	0.02	8	1	169	325
Trichloroethylene	2.0	0.0	0.29	95	35	205	129
	4.1	0.1	0.20	95	35	132	45
	6.0	0.1	0.21	95	35	209	238
Bis (2-ethylhexyl) phthalate	2.1	0.1	0.001	0.26	0.12	52	42
	4.0	0.1	0.001	0.26	0.12	56	41
	6.2	0.4	0.001	0.26	0.12	60	52
Toluene	2.0	0.0	0.31	59	14	66	87
	4.0	0.2	0.20	59	14	13	8
	6.0	0.0	0.14	59	14	≤10	0
Ethylbenzene	2.0	0.1	0.28	60	21	22	18
	4.0	0.1	0.18	60	21	47	96
	5.7	1.6	0.18	60	21	75	156

(continued)

TABLE 13. (continued)

Compound	SRT, days mean	SRT, days S.D.	F/M mean	Influent mg/l mean	Influent mg/l S.D.	Effluent µg/l mean	Effluent µg/l S.D.
Phenanthrene	2.0	0.2	0.001	0.56	0.21	≤10	--
	4.0	0.0	0.001	0.56	0.21	≤10	--
	6.1	0.1	0.001	0.56	0.21	≤10	
Chloroform	2.0	0.0	0.23	34.8	6.4	579	517
	4.0	0.1	0.11	34.8	6.4	407	431
	6.0	0.0	0.08	34.8	6.4	379	314
Carbon Tetrachloride	2.1	0.2	0.07	18.2	6.3	162	100
	4.1	0.2	0.04	18.2	6.3	225	117
	5.9	0.2	0.04	18.2	6.3	133	71
Naphthalene	2.0	0.0	0.03	6.9	2.9	≤100	0
	4.0	0.1	0.02	6.9	2.9	≤100	0
	6.0	0.0	0.01	6.9	2.9	≤100	0

TABLE 14. SLUDGE AGE, HYDRAULIC RESIDENCE TIME, AND MIXED LIQUOR SOLIDS FOR COMBINED SYSTEMS

Combined System	SRT, days mean	SRT, days S.D.	HRT, hours mean	HRT, hours S.D.	MLVSS, mg/l mean	MLVSS, mg/l S.D.
I	2.5	1.2	8.3	0.0	909	497
	3.6	2.4	8.5	0.0	947	408
	4.9	2.8	8.0	0.0	1549	851
II	2.1	0.7	8.2	1.8	706	284
	3.8	1.0	8.2	0.0	1150	328
	5.6	2.6	8.0	0.0	1231	380
III	2.1	0.1	8.2	0.0	798	268
	4.3	0.3	8.2	0.0	908	144
	6.0	0.5	8.0	0.0	1174	242
IV	2.0	0.0	8.2	0.0	1310	340
	4.0	0.2	8.2	0.0	1424	348
	5.9	0.1	8.0	0.0	1541	401
V	2.0	0.0	8.2	0.0	945	211
	4.0	0.1	8.2	0.0	1360	427
	6.0	0.0	8.0	0.0	1511	498
VI	2.1	0.1	8.5	0.2	579	162
	4.0	0.2	8.6	0.3	880	227
	5.9	0.6	8.2	0.2	1037	219
VII	2.0	0.1	8.4	0.1	654	109
	4.1	0.2	8.3	0.2	1273	380
	5.9	0.3	8.0	0.1	1171	307
VIII	2.0	0.0	8.3	0.0	944	182
	4.1	0.1	8.2	0.1	1258	122
	6.1	0.1	8.0	0.1	1368	113

TABLE 15. INFLUENT AND EFFLUENT BOD_5 FOR COMBINED SYSTEMS

Combined Systems	SRT, days mean	SRT, days S.D.	F/M mean	F/M S.D.	Influent BOD_5 mg/l mean	Influent BOD_5 mg/l S.D.	Effluent BOD_5 mg/l mean	Effluent BOD_5 mg/l S.D.
I	2.5	7.2	1.39	0.89	314	61	7.5	5.5
	3.6	2.4	1.19	0.84	316	62	4.1	2.4
	4.9	2.8	0.85	0.57	314	62	4.4	2.4
II	2.1	0.7	1.40	0.76	279	52	7.5	4.4
	3.8	1.0	0.79	0.42	279	52	6.3	3.8
	5.6	2.6	0.73	0.22	266	75	4.9	2.7
III	2.1	0.1	1.02	0.38	251	43	3.1	1.0
	4.3	0.3	0.83	0.22	248	38	3.1	1.6
	6.0	0.5	0.65	0.19	242	32	2.3	0.7
IV	2.0	0.0	0.63	0.15	268	28	2.6	1.0
	4.0	0.0	0.59	0.16	268	28	2.7	1.3
	5.9	0.1	0.55	0.14	267	28	2.5	0.9
V	2.0	0.0	0.73	0.20	227	29	4.7	1.6
	4.0	0.1	0.55	0.22	227	29	5.2	2.0
	6.0	0.0	0.52	0.24	227	29	5.7	2.7
VI	2.1	0.1	1.33	0.46	271	42	9.9	8.3
	4.0	0.2	0.87	0.27	270	42	6.9	6.3
	5.9	0.6	0.79	0.20	260	68	14.9	10.9
VII	2.0	0.1	0.98	0.22	217	25	2.4	1.3
	4.1	0.2	0.54	0.17	217	25	2.5	1.2
	5.9	0.3	0.55	0.16	217	25	2.8	1.6
VIII	2.0	0.0	1.02	0.29	317	34	4.4	2.4
	4.1	0.1	0.75	0.13	317	34	4.3	1.9
	6.1	0.1	0.70	0.09	317	34	3.5	1.3

TABLE 16. INFLUENT AND EFFLUENT TOC FOR COMBINED SYSTEMS

Combined Systems	SRT, days		F/M		Influent TOC mg/l		Effluent TOC mg/l	
	mean	S.D.	mean	S.D.	mean	S.D.	mean	S.D.
I	2.5	1.2	1.05	0.68	246	88	44	23
	3.6	2.4	0.95	0.65	246	89	30	13
	4.9	2.8	0.66	0.48	246	89	27	13
II	2.1	0.7	1.03	0.69	197	41	20	11
	3.8	1.0	0.52	0.16	197	41	19	16
	5.6	2.6	0.53	0.16	196	41	16	11
III	2.1	0.1	0.53	0.22	133	33	15	9
	4.3	0.3	0.45	0.16	133	33	15	9
	6.0	0.5	0.35	0.13	129	32	21	16
IV	2.0	0.0	0.42	0.10	176	18	18	6
	4.0	0.0	0.39	0.11	176	18	19	8
	5.9	0.1	0.37	0.12	176	18	21	5
V	2.0	0.0	0.46	0.13	143	22	11	6
	4.0	0.1	0.34	0.14	143	22	10	3
	6.0	0.0	0.32	0.13	143	22	9	4
VI	2.1	0.1	0.89	0.26	169	23	22	10
	4.0	0.2	0.58	0.16	168	23	17	6
	5.9	0.6	0.49	0.13	169	23	22	8
VII	2.0	0.1	0.65	0.11	144	20	15	5
	4.1	0.2	0.40	0.13	149	16	17	8
	5.9	0.3	0.38	0.11	147	18	18	8
VIII	2.0	0.0	0.54	0.12	170	30	22	7
	4.1	0.1	0.40	0.05	170	30	20	4
	6.1	0.1	0.37	0.06	170	30	18	5

TABLE 17. INFLUENT AND EFFLUENT COD FOR COMBINED SYSTEMS

Combined Systems	SRT, days		F/M		Influent COD mg/l		Effluent COD mg/l	
	mean	S.D.	mean	S.D.	mean	S.D.	mean	S.D.
I	2.5	1.2	3.44	2.56	574	32	86	30
	3.6	2.4	2.18	0.68	574	32	45	17
	4.9	2.8	1.80	1.15	574	32	27	7
II	2.1	0.7	2.16	0.90	565	45	53	18
	3.8	1.0	2.47	2.20	565	45	70	15
	5.6	2.6	1.71	0.47	565	45	65	17
III	2.1	0.1	1.67	0.84	401	137	45	47
	4.3	0.3	1.38	0.66	394	124	23	8
	6.0	0.5	1.10	0.58	404	146	25	16
IV	2.0	0.0	1.11	0.21	454	61	32	14
	4.0	0.0	1.02	0.26	454	61	24	12
	5.9	0.1	0.89	0.31	454	61	29	13
V	2.0	0.0	1.18	0.22	429	34	35	6
	4.0	0.1	0.96	0.29	429	34	36	14
	6.0	0.0	0.81	0.21	429	34	32	10
VI	2.1	0.1	2.88	1.16	577	111	53	18
	4.0	0.2	1.86	0.47	574	104	37	12
	5.9	0.6	1.67	0.45	574	104	60	28
VII	2.0	0.1	2.07	0.42	469	50	29	10
	4.1	0.2	1.25	0.56	474	49	31	8
	5.9	0.3	1.24	0.28	469	50	30	11
VIII	2.0	0.0	1.31	0.28	409	21	37	7
	4.1	0.1	0.97	0.11	409	21	31	7
	6.1	0.1	0.90	0.06	406	22	38	23

TABLE 18. EFFLUENT SOLIDS, SLUDGE VOLUME INDEX AND OXYGEN UPTAKE RATE FOR COMBINED SYSTEMS

Combined Systems	SRT, days mean	SRT, days S.D.	Effluent VSS, mg/l mean	Effluent VSS, mg/l S.D.	SVI Range	O_2 Uptake mg/gm/hr mean	O_2 Uptake mg/gm/hr S.D.
I	2.5	1.2	83	84	---	13.1	8.8
	3.6	2.4	70	74	---	10.6	3.2
	4.9	2.8	107	110	---	6.3	2.1
II	2.1	0.7	52	56	96- 163	15.0	8.0
	3.8	1.0	23	15	88- 108	13.3	3.6
	5.6	2.6	36	45	61- 88	7.3	4.8
III	2.1	0.1	19	11	90-1000	15.9	1.9
	4.3	0.3	26	10	100- 800	15.4	1.7
	6.0	0.5	17	16	60- 675	13.1	1.5
IV	2.0	0.0	7	8	154- 694	18.9	6.2
	4.0	0.2	23	22	211- 951	18.0	7.2
	5.9	0.1	17	24	290- 842	15.5	4.1
V	2.0	0.0	8	8	103- 943	15.0	8.7
	4.0	0.1	8	9	79-1000	13.9	8.3
	6.0	0.0	8	7	83- 440	11.3	4.6
VI	2.1	0.1	17	16	129-1520	19.5	8.5
	4.0	0.2	18	15	122-1605	16.3	7.5
	5.9	0.6	22	16	494-1240	12.9	5.7
VII	2.0	0.1	6	4	129-2202	21.3	6.1
	4.1	0.2	4	5	260-1175	15.5	4.2
	5.9	0.3	4	4	441-1548	16.0	3.1
VIII	2.0	0.0	17	13	56- 378	12.3	1.8
	4.1	0.1	10	6	89- 625	11.1	0.9
	6.1	0.1	9	6	331- 680	10.8	1.6

TABLE 19. INFLUENT AND EFFLUENT CONCENTRATIONS OF SPECIFIC COMPOUNDS FOR COMBINED SYSTEMS

Combined System	SRT, days mean	SRT, days S.D.	F/M mean	Influent Conc. mg/l mean	Influent Conc. mg/l S.D.	Effluent Conc. μg/l mean	Effluent Conc. μg/l S.D.
I. Tetrachloroethane	2.5	1.2	0.16	52	14	3,600	--
Nitrobenzene			0.12	38	5	22,800	5,000
2,4 Dichlorophenol			0.08	24	2	9,000	--
Tetrachloroethane	3.6	2.4	0.16	52	14	3,200	--
Nitrobenzene			0.11	38	5	18,500	10,900
2,4 Dichlorophenol			0.07	24	2	7,500	--
Tetrachloroethane	4.9	2.8	0.10	52	14	2,000	--
Nitrobenzene			0.07	38	5	24,800	2,000
2,4 Dichlorophenol			0.05	24	2	5,500	--
II. Acrylonitrite	2.1	0.7	0.13	31	--	30	--
Acrolein			0.13	31	--	30	--
1,2 Dichloropropane			0.20	48	--	50	--
Acrylonitrite	3.8	1.0	0.08	31	--	30	--
Acrolein			0.08	31	--	30	--
1,2 Dichloropropane			0.12	48	--	200	--
Acrylonitrite	5.6	2.6	0.08	31	--	30	--
Acrolein			0.08	31	--	30	--
1,2 Dichloropropane			0.12	48	--	170	--
III. Benzene	2.1	0.1	0.14	39	12	≤50	--
Methylene Chloride			0.21	56	24	≤50	--
Ethyl Acetate			0.23	63	19	≤50	--
Benzene	4.3	0.3	0.13	39	12	≤50	--
Methylene Chloride			0.18	56	24	≤50	--
Ethyl Acetate			0.20	63	19	≤50	--
Benzene	6.0	0.5	0.10	39	12	≤50	--
Methylene Chloride			0.14	56	24	≤50	--
Ethyl Acetate			0.16	63	19	≤50	--

(Continued)

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TABLE 19. (continued)

Combined System	SRT, days mean	SRT, days S.D.	F/M mean	Influent Conc. mg/l mean	Influent Conc. mg/l S.D.	Effluent Conc. µg/l mean	Effluent Conc. µg/l S.D.
IV. 1,2 Dichlorobenzene	2.0	0.0	0.02	10	2	≤50	--
1,2 Dichloroethane			0.14	63	26	1,150	880
Phenol			0.15	65	8	≤10	--
1,2 Dichlorobenzene	4.0	0.2	0.02	10	2	≤50	--
1,2 Dichlorothane			0.13	63	26	950	810
Phenol			0.13	65	8	≤10	--
1,2 Dichlorobenzene	5.9	0.1	0.02	10	2	≤50	--
1,2 Dichloroethane			0.12	63	26	1,110	1,070
Phenol			0.13	65	8	≤10	--
V. 2,4 Dinitrophenol	2.0	0.0	0.10	32	8	≤250	--
1,3 Dichlorobenzene			0.06	20	8	17	15
1,1,1 Trichloroethane			0.19	60	24	154	151
2,4 Dinitrophenol	4.0	0.1	0.07	32	8	≤250	--
1,3 Dichlorobenzene			0.04	20	8	22	29
1,1,1 Trichloroethane			0.13	60	24	68	93
2,4 Dinitrophenol	6.0	0.0	0.06	32	8	≤250	--
1,3 Dichlorobenzene			0.04	20	8	25	42
1,1,1 Trichloroethane			0.12	60	24	94	96
VI. Pentachlorophenol	2.1	0.1	0.02	3.7	0.8	152	292
Trichloroethylene			0.32	66	24	≤100	--
Bis(2-ethylhexyl)			0.002	0.35	0.07	≤50	--
Pentachlorophenol	4.0	0.2	0.01	3.7	0.8	125	167
Trichloroethylene			0.21	66	24	≤100	--
Bis(2-ethylhexyl)			0.001	0.35	0.07	≤50	--
Pentachlorophenol	5.9	0.6	0.01	3.7	0.8	83	65
Trichloroethylene			0.19	66	24	≤100	--
Bis(2-ethylhexyl)			0.001	0.35	0.07	≤50	--

(continued)

TABLE 19. (continued)

	Combined System	SRT, days mean	SRT, days S.D.	F/M mean	Influent Conc. mg/l mean	Influent Conc. mg/l S.D.	Effluent Conc. µg/l mean	Effluent Conc. µg/l S.D.
VII.	Toluene	2.0	0.1	0.07	16.8	6.0	≤10	--
	Ethyl benzene			0.08	19.3	5.9	≤10	--
	Phenanthrene			0.001	0.19	0.04	≤10	--
	Toluene	4.1	0.2	0.04	16.8	6.0	≤10	--
	Ethyl benzene			0.04	19.3	5.9	≤10	--
	Phenanthrene			0.001	0.19	0.04	≤10	--
	Toluene	5.9	0.3	0.04	16.8	6.0	≤10	--
	Ethyl benzene			0.05	19.3	5.9	≤10	--
	Phenanthrene			0.001	0.19	0.04	≤10	--
VIII.	Chloroform	2.0	0.0	0.04	13.7	6.2	226	180
	Carbon tetrachloride			0.02	7.1	5.5	18	22
	Naphthalene			0.01	2.3	0.5	≤50	--
	Chloroform	4.1	0.1	0.03	13.7	6.2	248	196
	Carbon tetrachloride			0.02	7.1	5.5	23	23
	Naphthalene			0.01	2.3	0.5	≤50	--
	Chloroform	6.1	0.1	0.03	13.7	6.2	123	75
	Carbon tetrachloride			0.02	7.1	5.5	7	8
	Naphthalene			0.01	2.3	0.5	≤50	--

5-30

BIOKINETIC CONSTANTS

Biokinetic constants for the activated sludge design models are determined by graphical means. The data plots required for these determinations are shown in Figures 10-13. Figure 10 is the data plot required for Eckenfelder's K_e'. Figure 11 is the data plot for determining Y_t and k_d. Figure 12 is the data plot for μ_{max} and K_s which are used in Gaudy's design equation. Figure 13 is the data plot for determining K and K_s which are used in the Lawrence and McCarty design model. These data plots are for the control BOD_5 data. It is seen that when the data for each sampling period are used there is a great deal of variability. These type of plots are to be expected when all of the data are plotted. However, this variability is usually eliminated by using mean values. Examples of this method are shown in Figures 14-17. Figure 14 shows the graphical determination of Eckenfelder's K_e' using mean values. The slope of the line is K_e'. Figure 15 shows the graphical determination of Y_t and k_d using mean values. The slope of the line is Y_t and k_d is equal to the y-intercept. Figure 16 illustrates the graphical determination of μ_{max} and K_s using mean values. The y-intercept is equal to $1/\mu_{max}$ and the slope of the line is equal to K_s/μ_{max}. Figure 17 shows the graphical determination of K and K_s using mean values. The y-intercept is equal to 1/K and the slope of the line is equal to K_s/K.

The graphical determination of the biokinetic constants using mean values does provide good mean biokinetic constants. However, this procedure does not take into account the variability of the response of the biological system. Thus, a new procedure has been developed for accounting for this variability.

During the treatability studies the hydraulic retention time (t), the flow rate (F), and the SRT were kept constant. The parameters that varied were effluent substrate concentration (S_e) and the mixed liquor volatile suspended solids (X). The influent BOD concentration (S_i) also varied, even though attempts were made to keep it constant for each wastewater. Probability plots of these parameters can be developed over the data collection period to evaluate the variability observed for these parameters. However, the specific substrate utilization rate, $U = \frac{S_i - S_e}{Xt}$, contains the constant t and the variables S_i, S_e, and X, and a probability plot of U takes into account the combined effects of these variables at the specific operating conditions observed.

A probability plot of U for the control systems at 2, 5, and 8-day SRT's is shown in Figure 18. A probability plot of $S_i \cdot U$ for these same control systems is shown in Figure 19. A probability plot of the S_e obtained from these same control systems is shown in Figure 20. From these three figures any desired probability level can be evaluated, for example, at 5 and 95 percent the corresponding values of U, $S_i \cdot U$, and S_e are determined at that probability level. These probability levels can then be used to evaluate the variability expected in the biokinetic constants or coefficients developed to describe the treatability of a given wastewater, as shown in Figures 21, 22, 23, and 24 for the control systems.

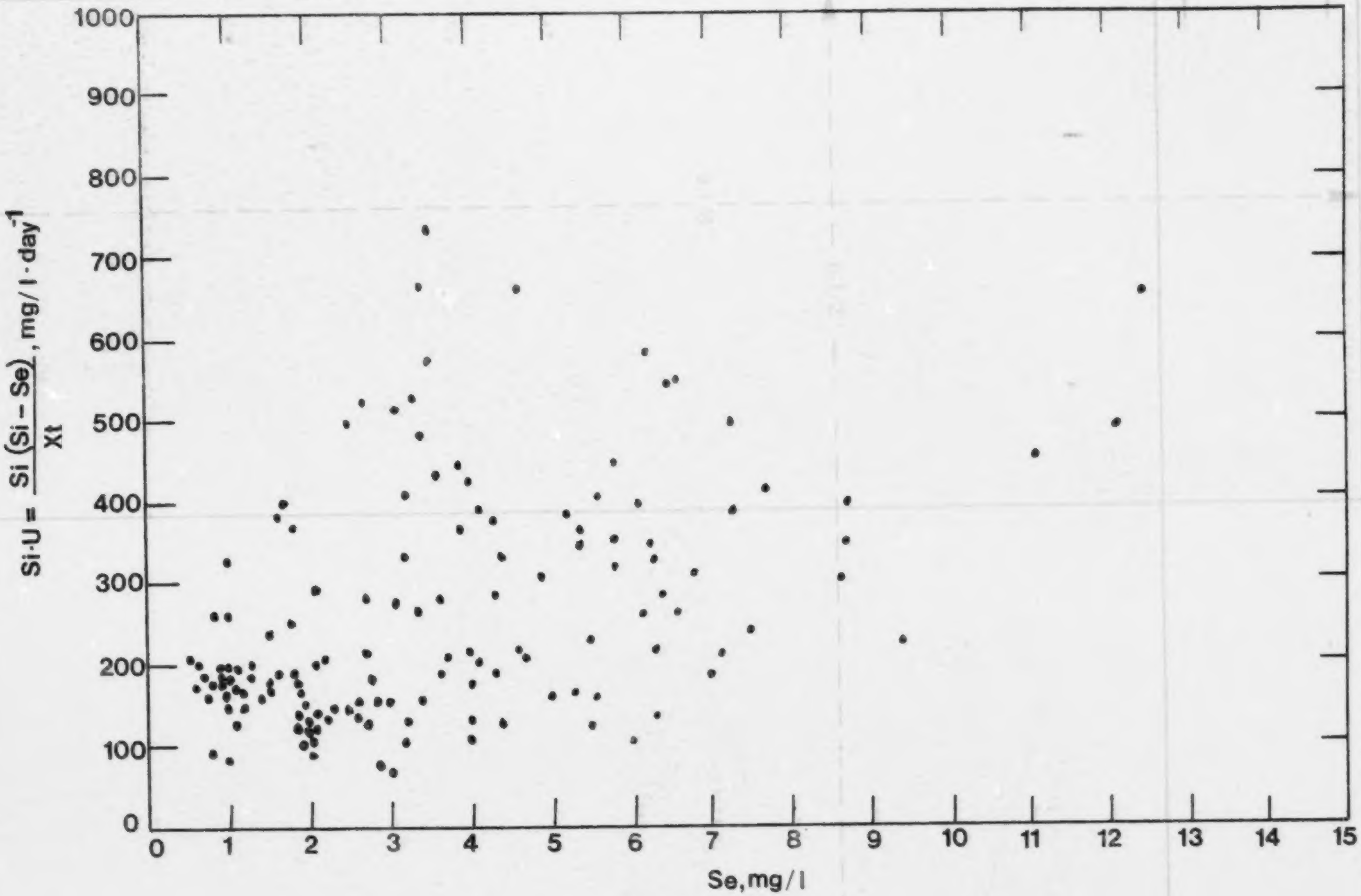

Figure 10.—Plot of $S_i(S_i - S_e)/Xt$ versus S_e for control system (BOD_5).

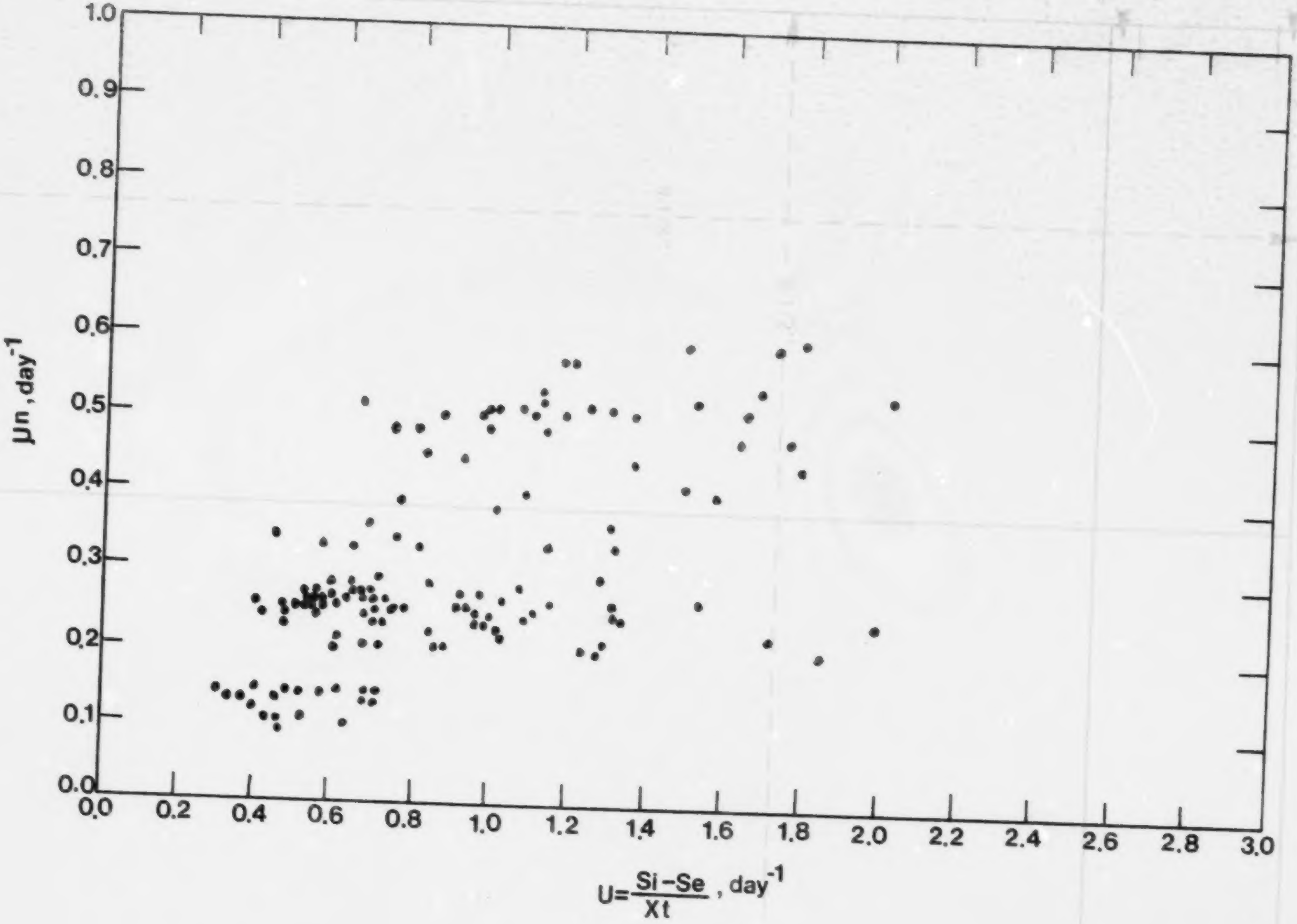

Figure 11. Plot of μ_n versus $S_i - S_e/Xt$ for control system (BOD_5).

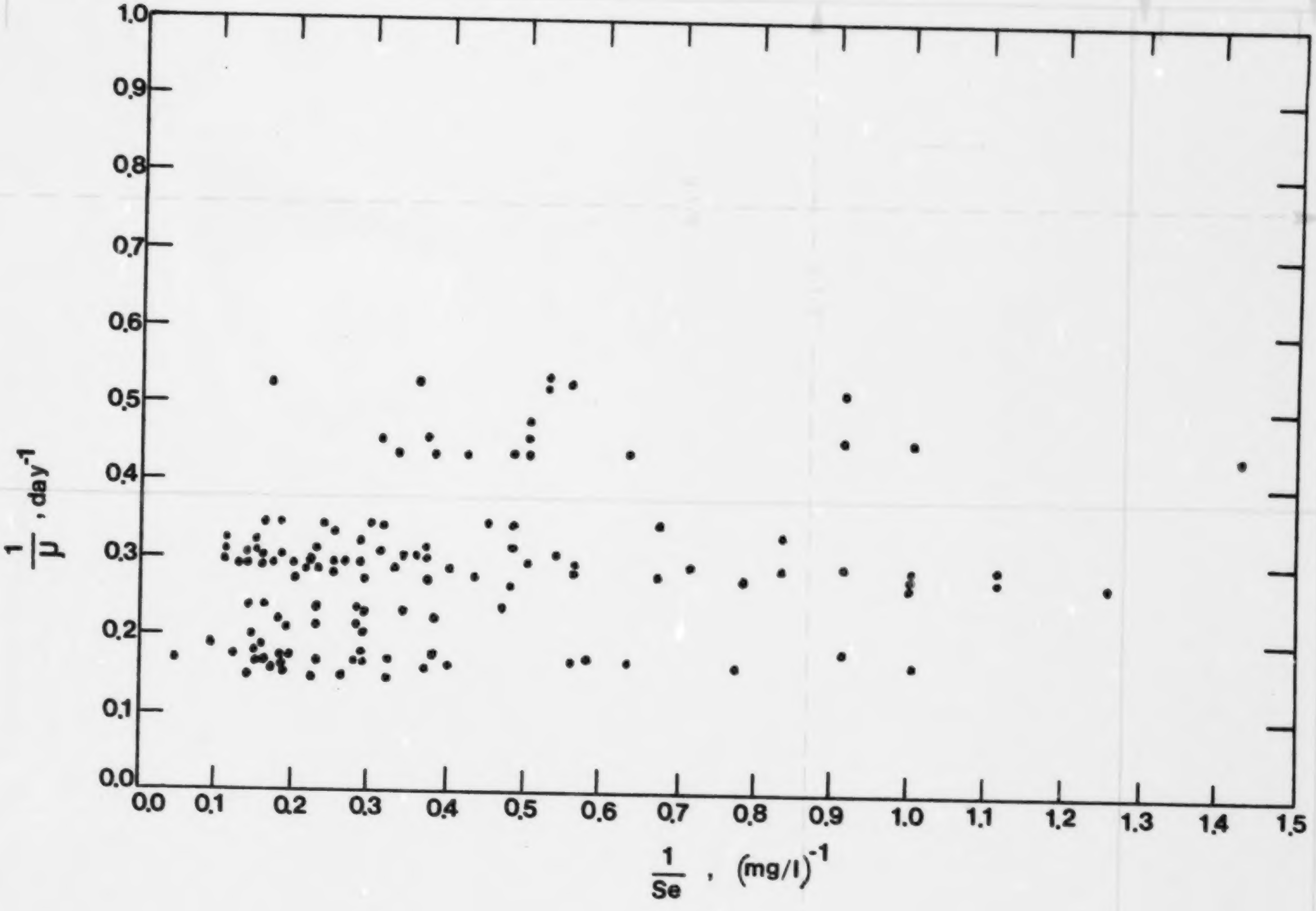

Figure 12. Plot of $1/\mu$ versus $1/S_e$ for control system (BOD_5).

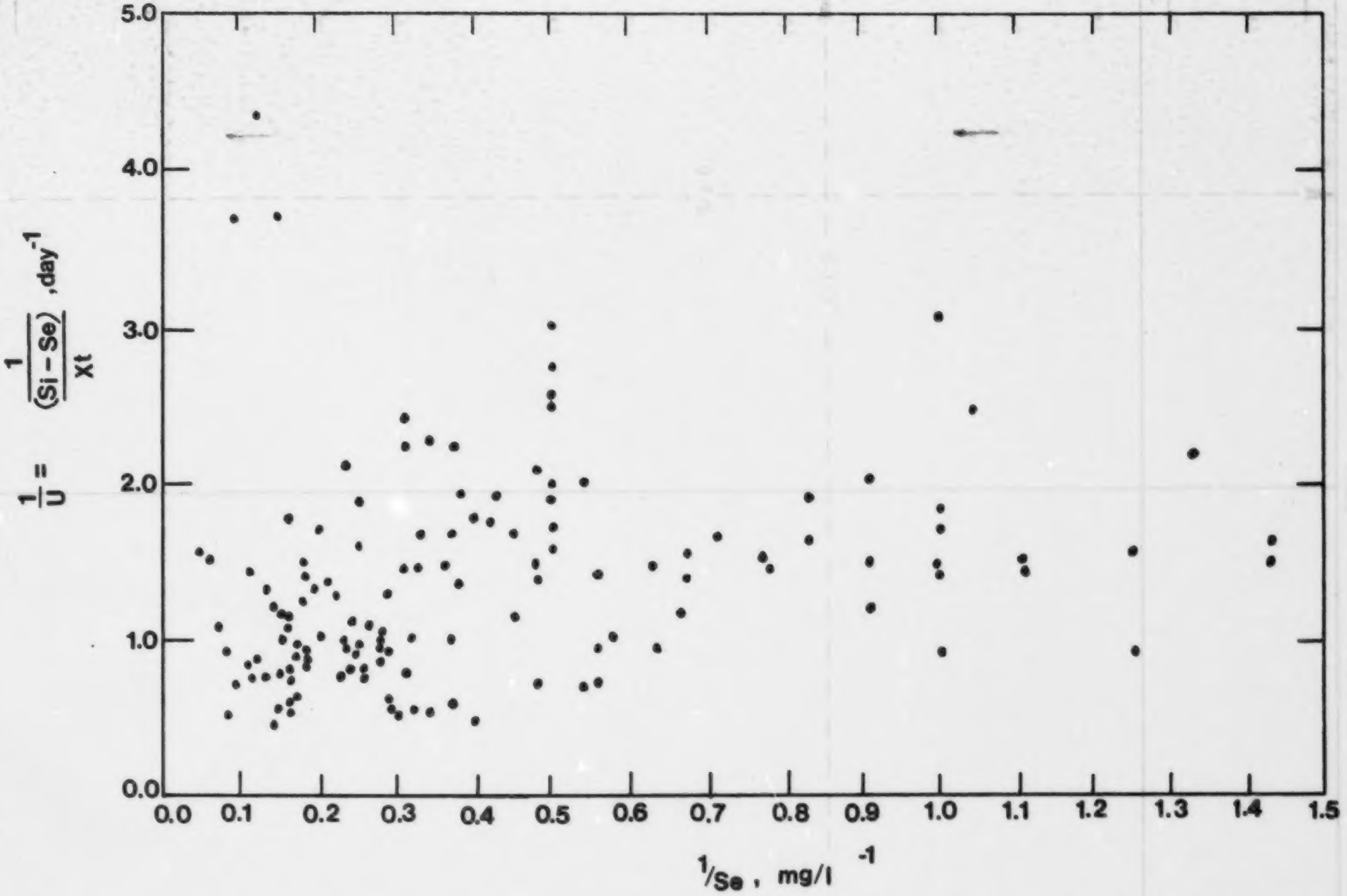

Figure 13. Plot of $1/S_i$ - S_e/Xt versus $1/S_e$ for control system (BOD_5).

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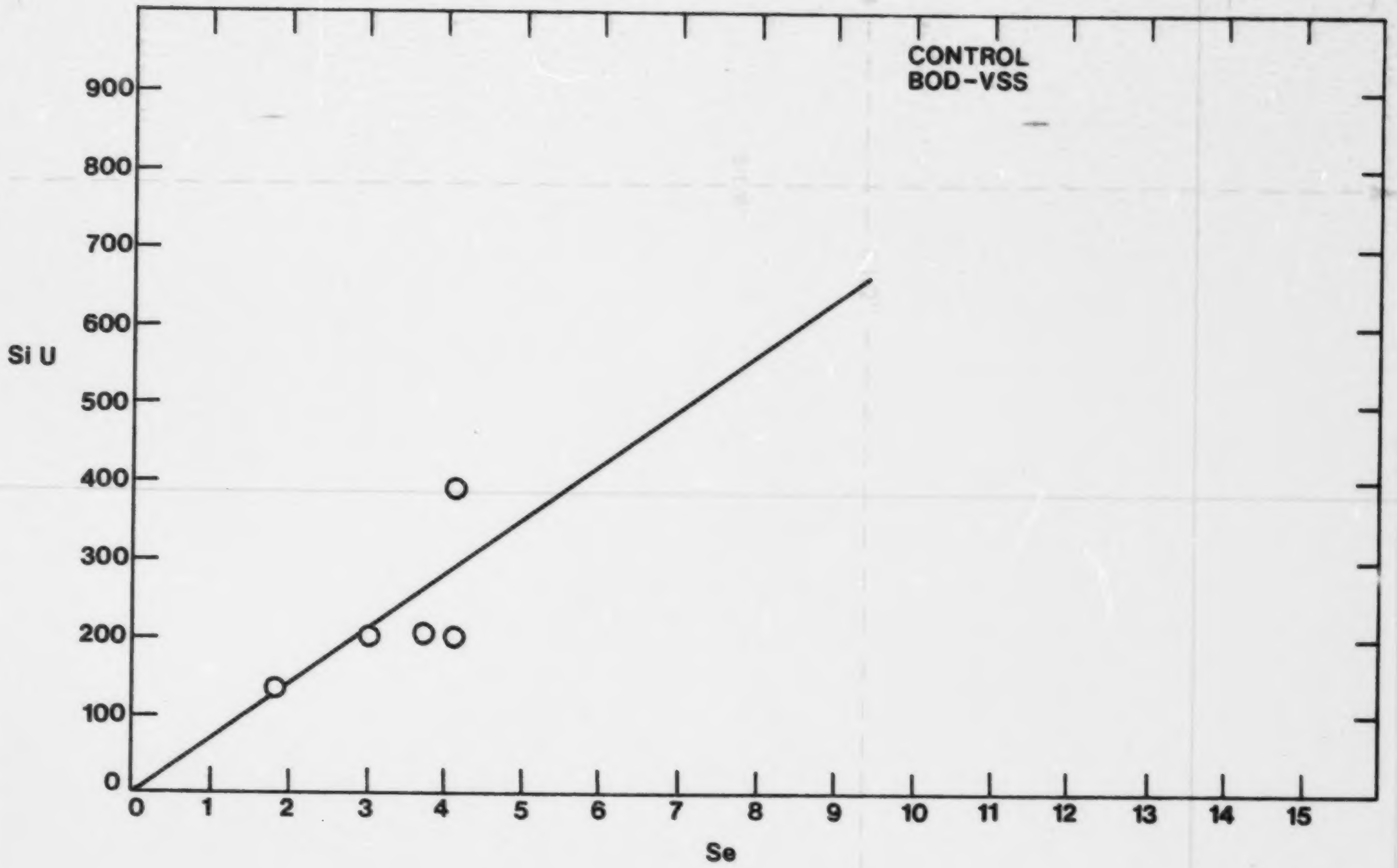

Figure 14. Graphical determination of K_e' with mean values.

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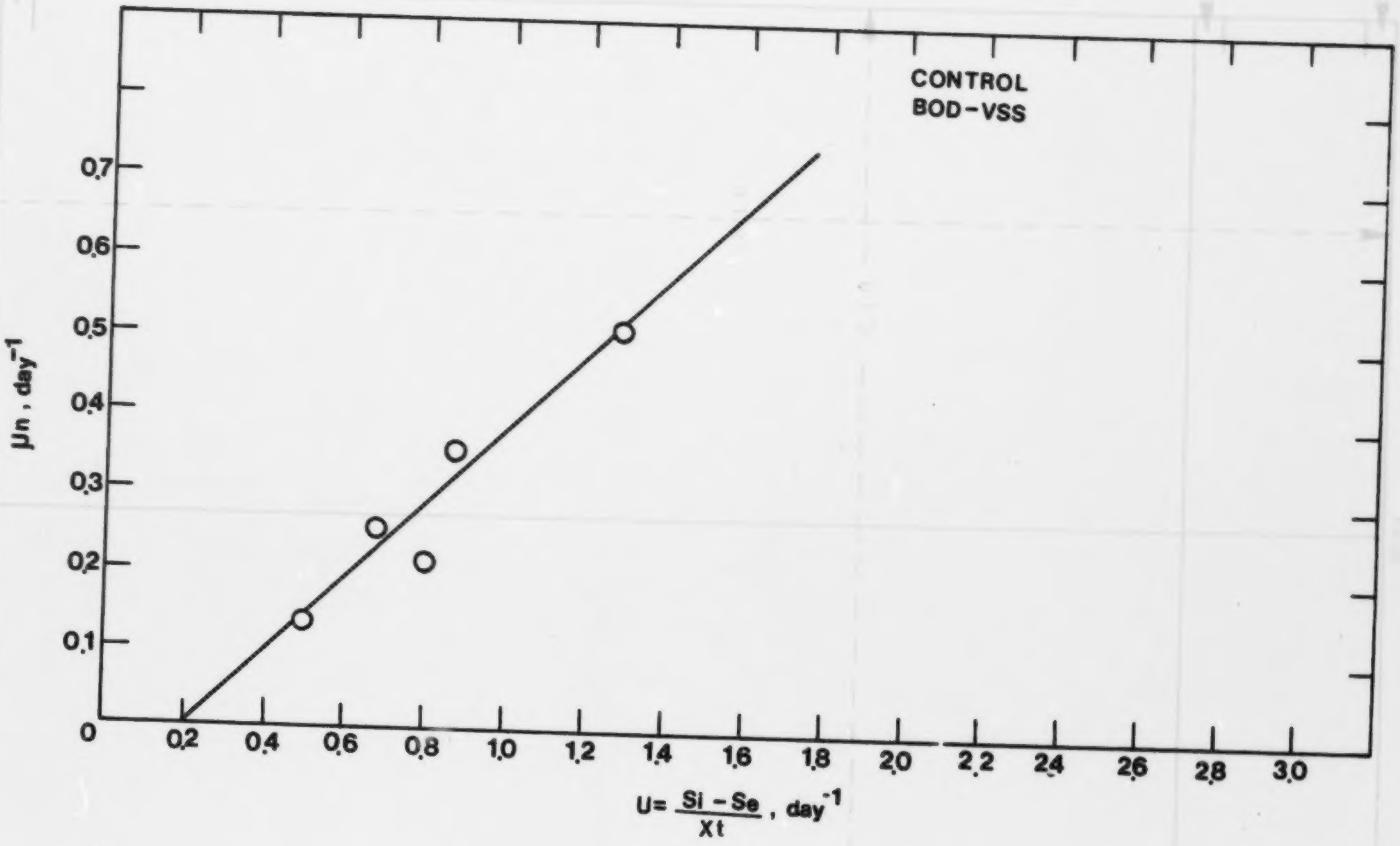

Figure 15. Graphical determination of Y_t and k_d with mean values.

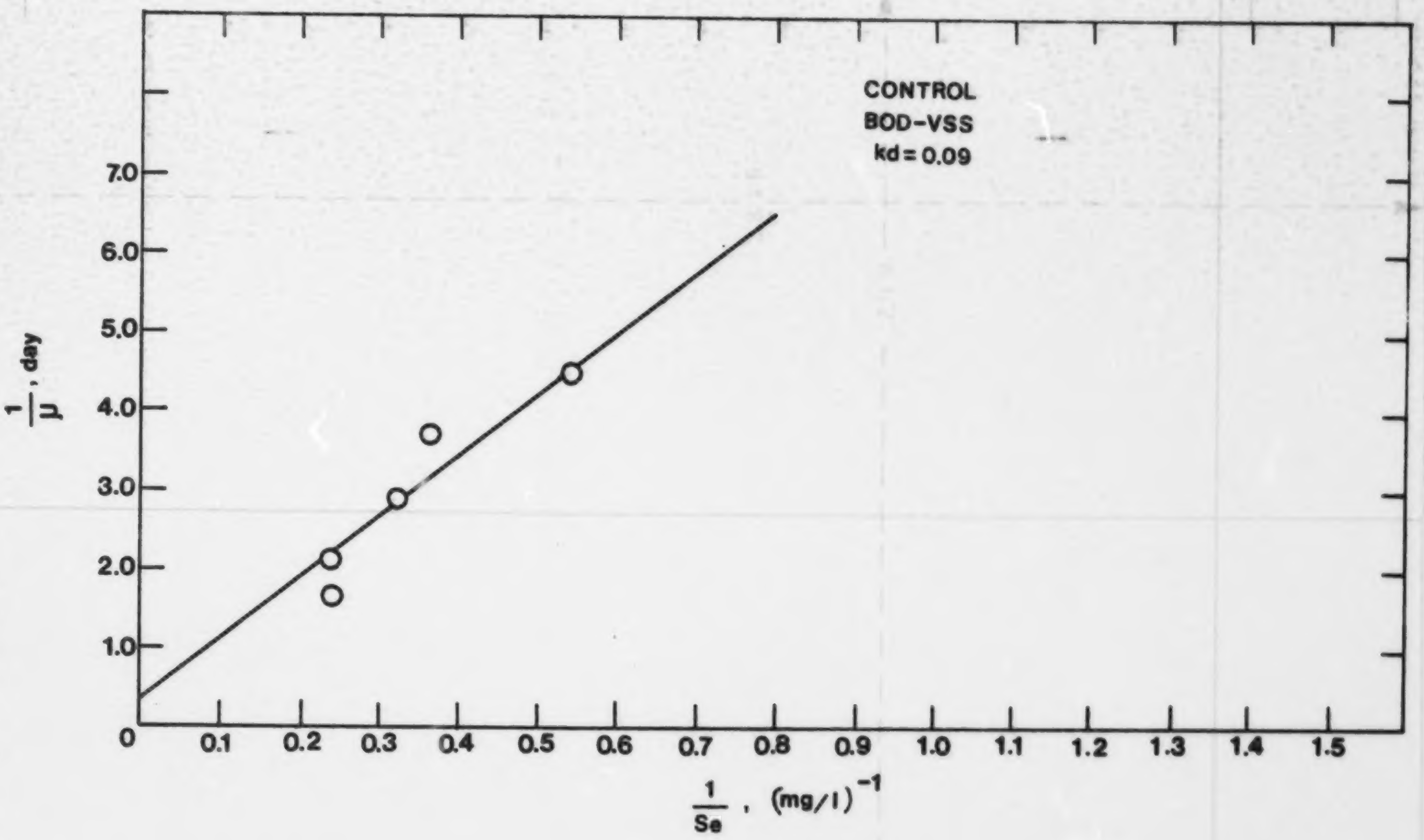

Figure 16. Graphical determination of μ_{max} and K_s with mean values.

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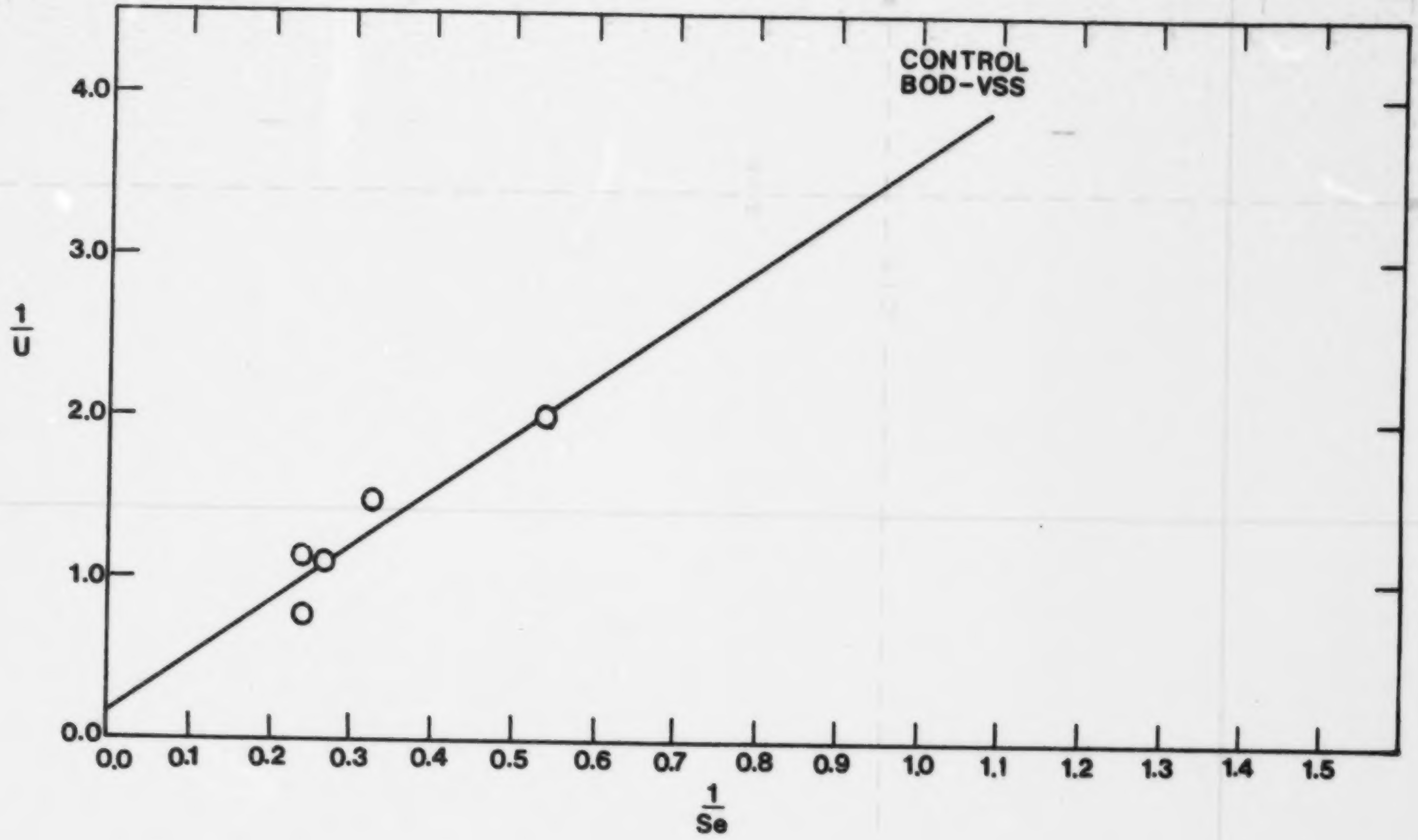

Figure 17. Graphical determination of K and K_S with mean values.

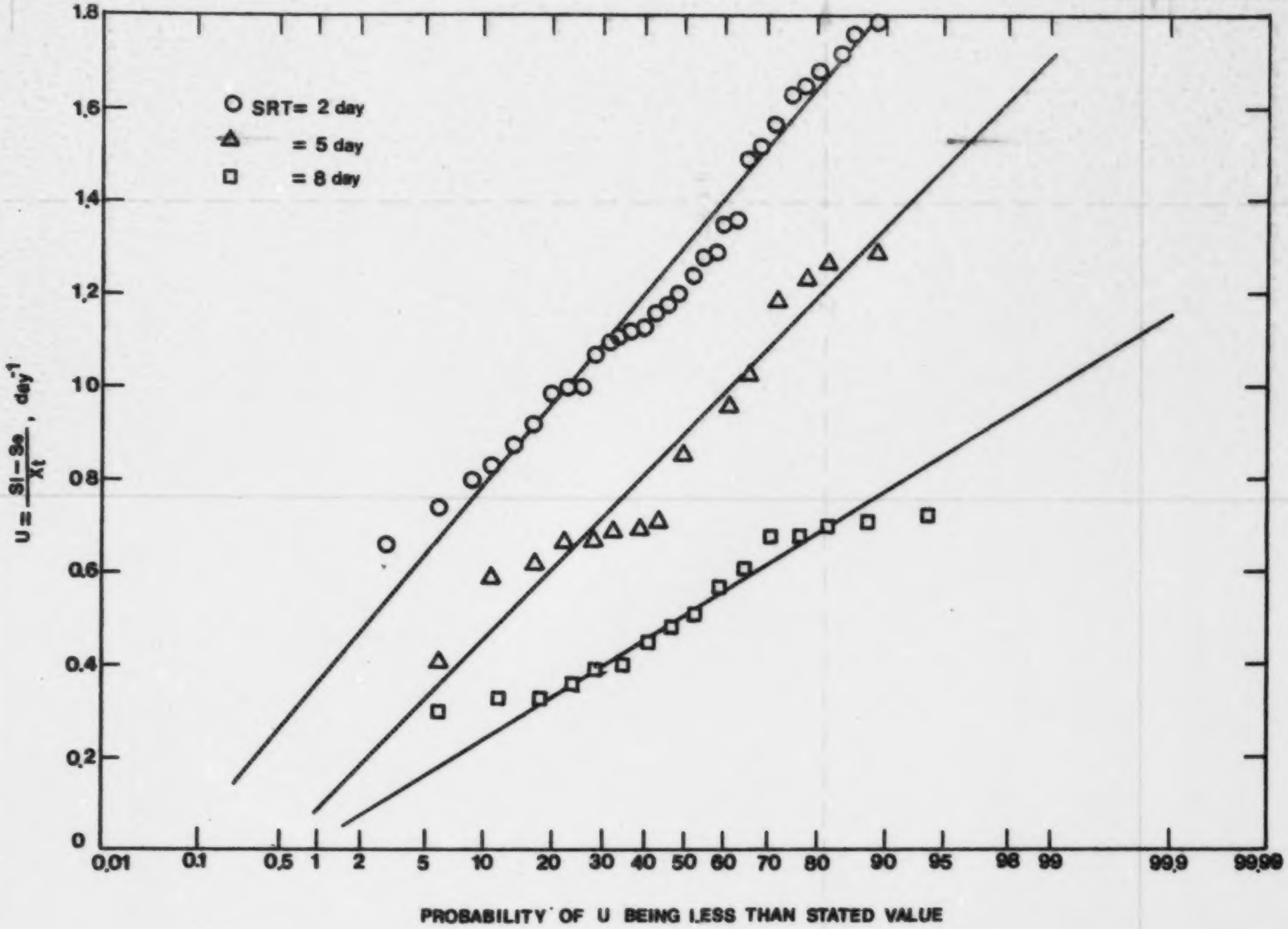

Figure 18. Observed specific substrate utilization (BOD_5) variability for control activated sludge systems.

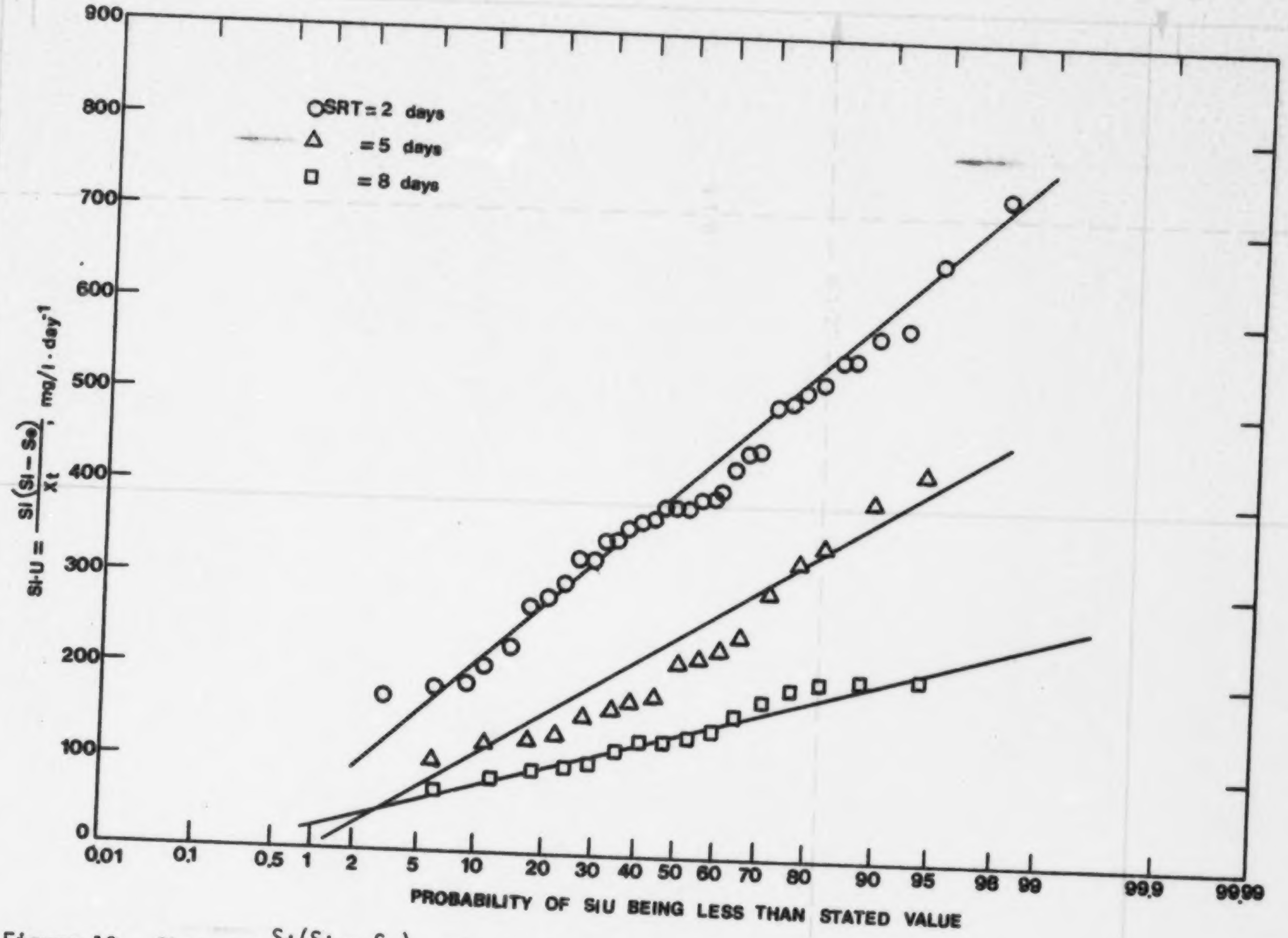

Figure 19. Observed $\frac{S_i(S_i - S_e)}{Xt}$ (BOD_5) variability for control activated sludge systems.

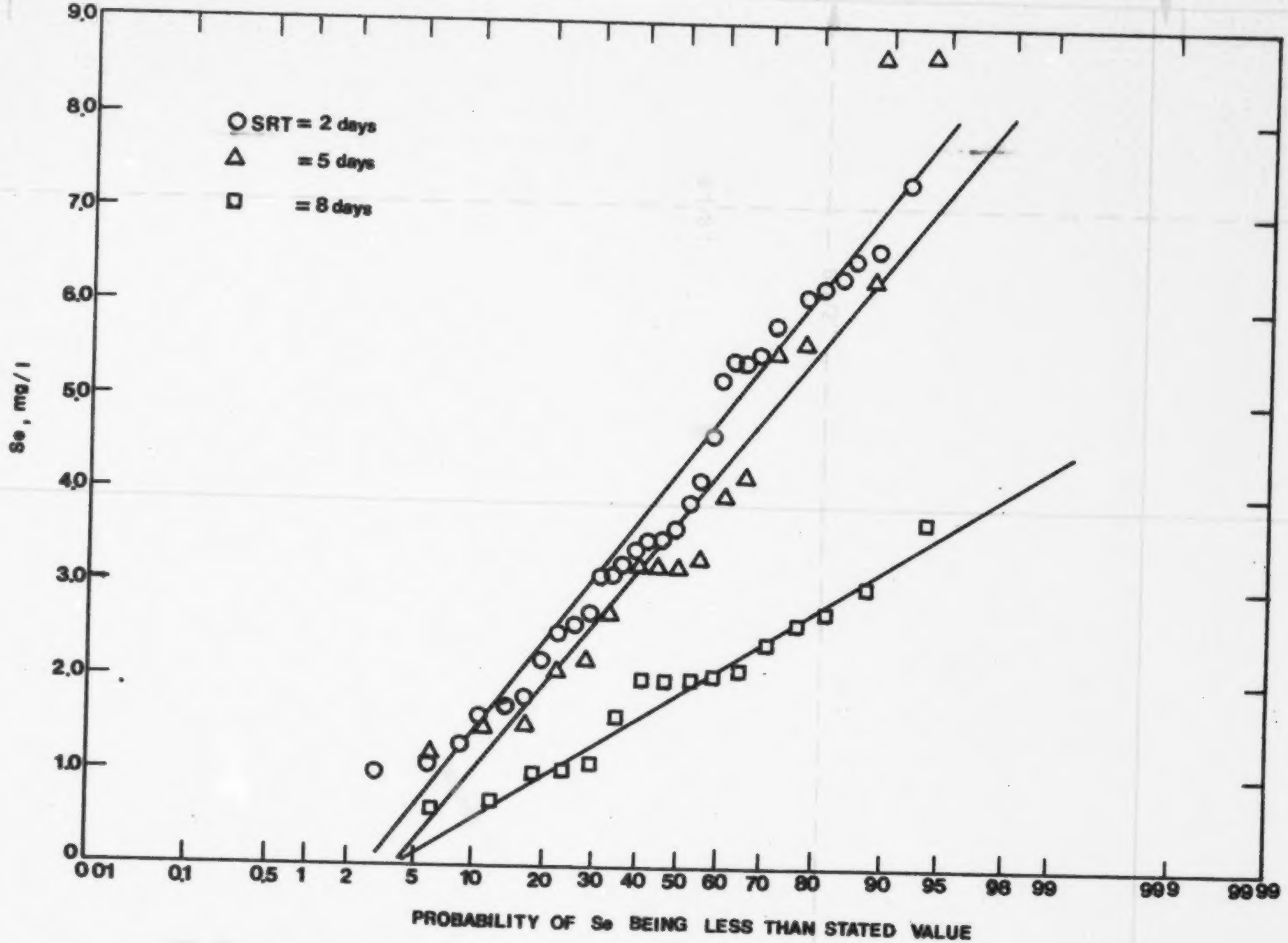

Figure 20. Observed effluent BOD_5 variability for control activated sludge systems.

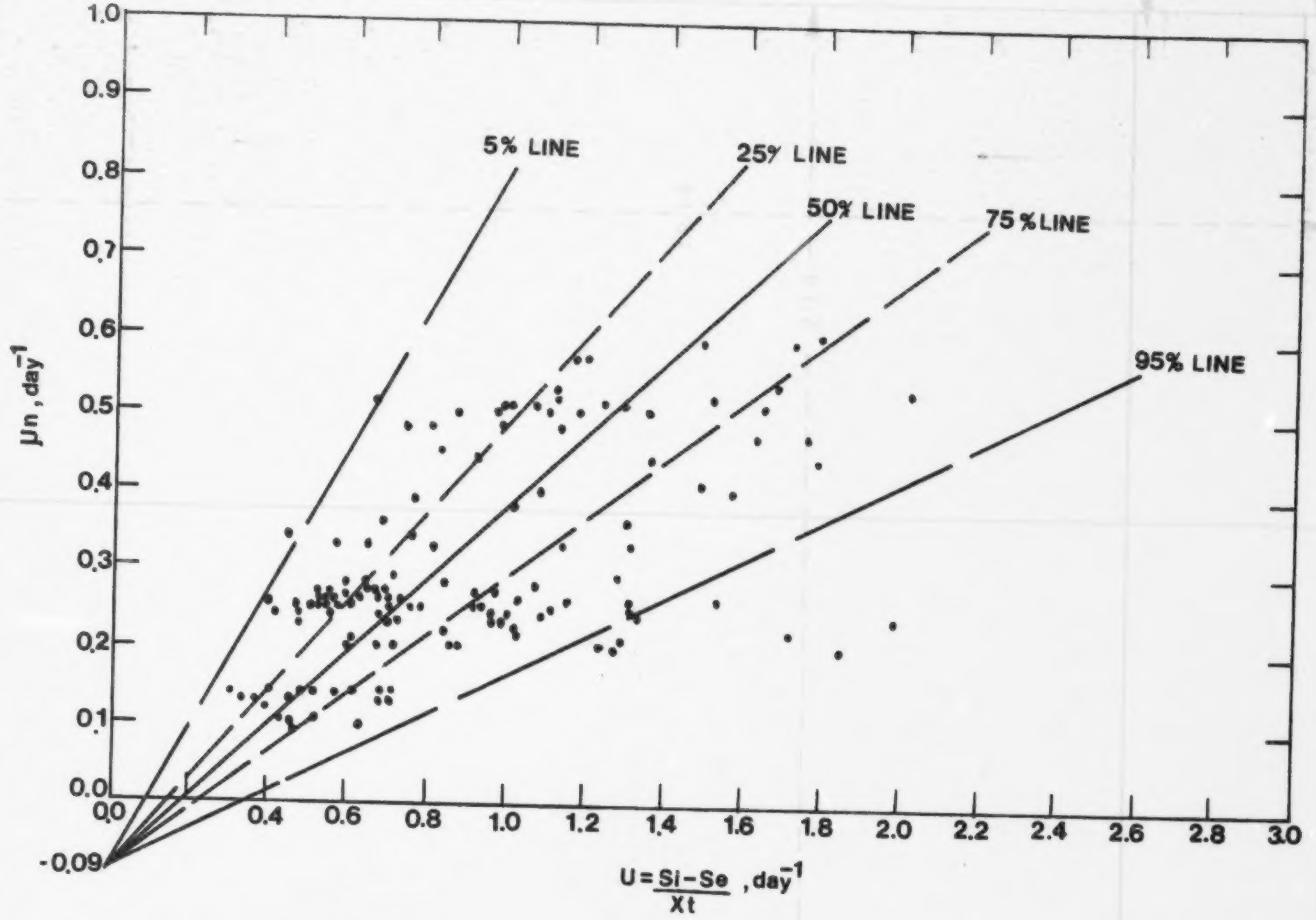

Figure 21. Graphical determination of Y_t and k_d (BOD_5) at different probability levels for control activated sludge systems.

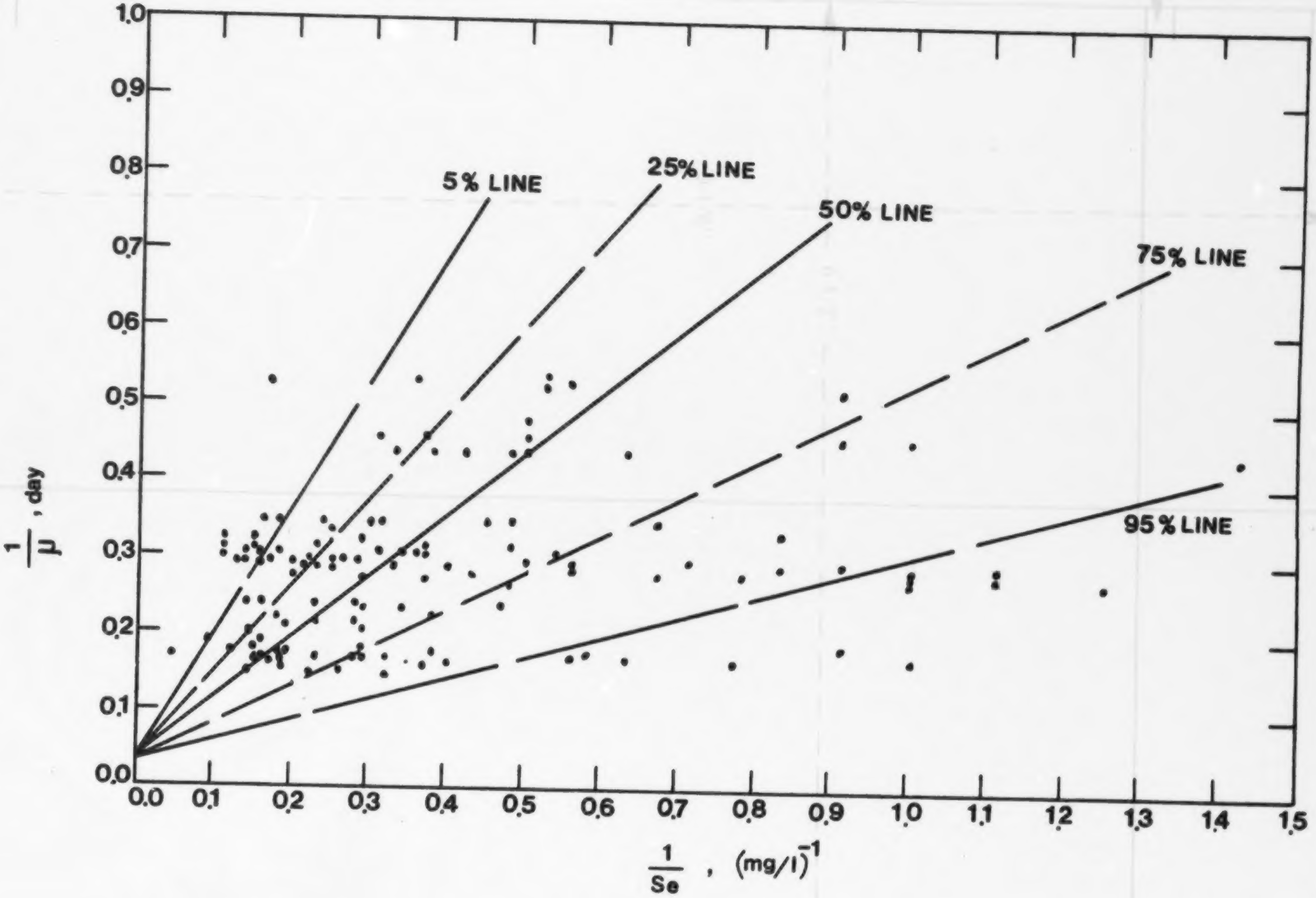

Figure 22. Graphical determination of μ_{max} and K_s (BOD_5) at different probability levels for control activated sludge systems.

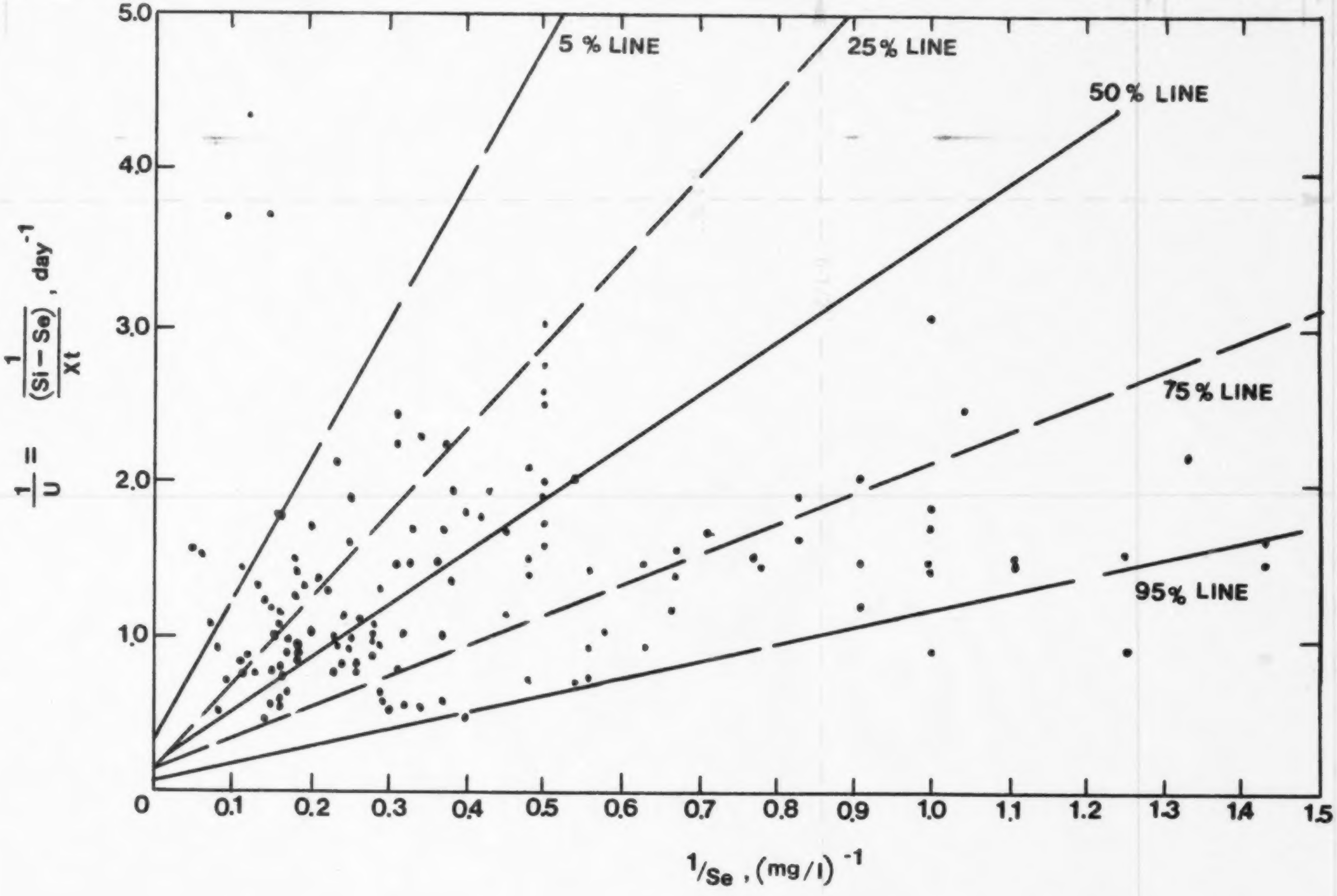

Figure 23. Graphical determination of K and K_S (BOD_5) at different probability levels for control activated sludge systems.

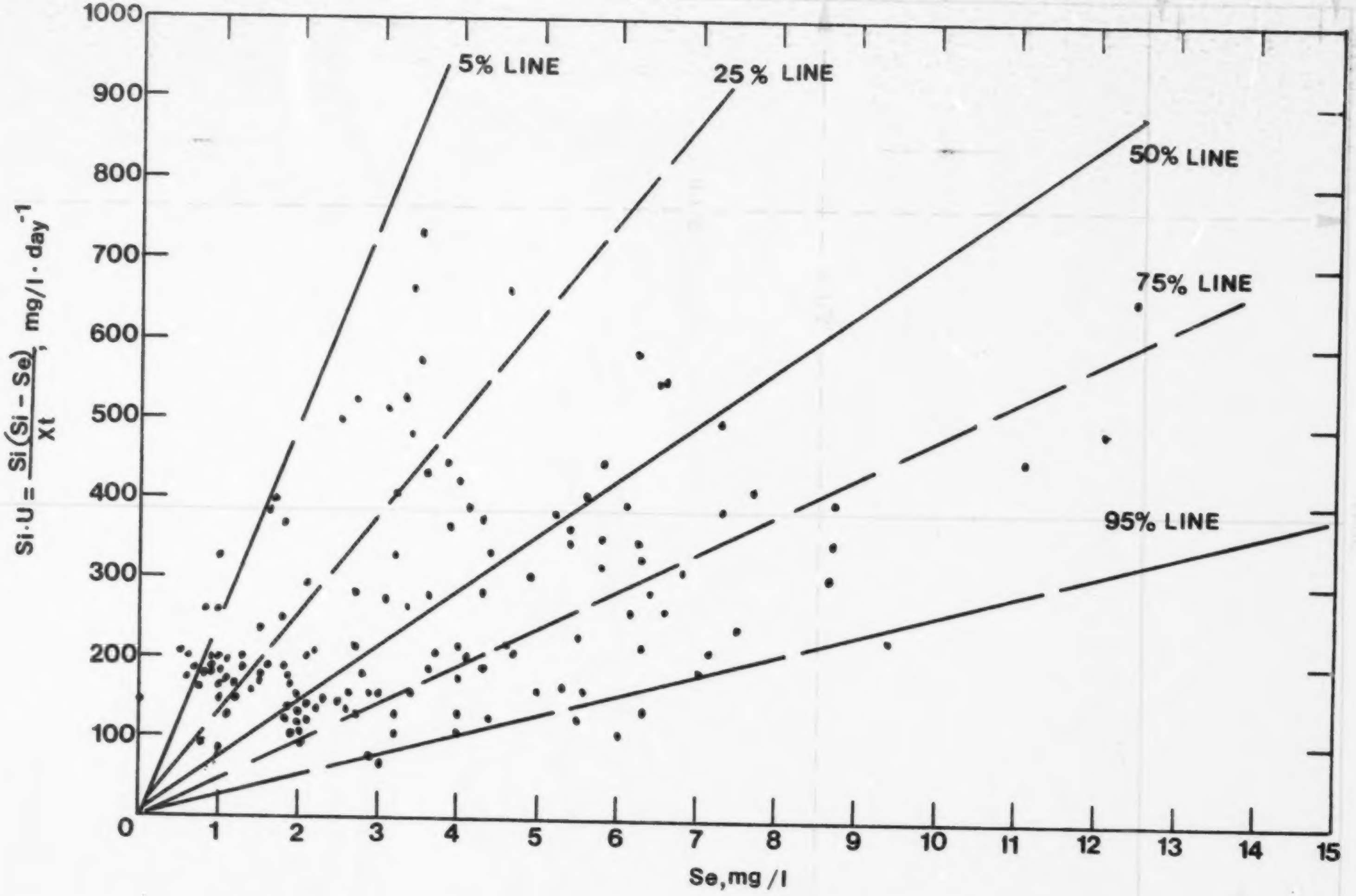

Figure 24. Graphical determination of K_e' (BOD_5) at different probability levels for control activated sludge systems.

In Figure 21, the net specific growth rate is plotted as a function of the specific substrate utilization rate for determination of the true cell yield (Y_t) and the endogeneous decay or maintenance energy coefficient (k_d) as used in all the kinetic design models. Y_t is the slope of the line and k_d is the Y-axis intercept. The scatter of the data as shown in this plot was typical for the data analysis for determination of all the biokinetic constants for all the wastewaters studied whether in terms of BOD, TOC or COD. This type of scatter is also typical for treatability studies with actual industrial and municipal wastewaters due to the inherent variability of hetergeneous biological populations.

The biokinetic constants Y_t and k_d can be determined for any probability level desired, as shown in Figure 21 for the 5, 25, 50, 75, and 95 percent probability levels. The desired probability value of U can be selected from Figure 18 for the different μ_n's or SRT's investigated and plotted on Figure 21 against the respective μ_n or SRT to yield the biokinetic constants Y_t and k_d at that specific probability level. If μ_n or SRT could not be maintained constant during the treatability study, a probability plot of μ_n or SRT would also be required to develop the lines shown in Figure 21. When μ_n is controlled as a constant, the probability line is a horizontal line, and μ_n is the same value at all probability levels.

An interesting aspect of Figure 21 is the variability of Y_t due to the biological population dynamics throughout the study period while k_d remains constant. This is due to the fact that as μ_n increases or SRT decreases the specific substrate utilization rate becomes more variable. As the μ_n is decreased the system becomes more stable with less variability in U. This observation was made with all the wastewaters investigated and points out that k_d can be treated as a true biokinetic constant, but Y_t varies with the population dynamics and should really be treated as a biokinetic coefficient rather than a constant.

In Figure 22, the reciprocal of the specific growth rate (μ) is plotted against the reciprocal of the effluent substrate concentration (S_e) for determination of the maximum specific growth rate (μ_{max}) and the saturation constant (K_s) as used in the Gaudy design model. The y-axis intercept is the reciprocal of μ_{max}, and the slope is equal to K_s/μ_{max}. Again, the scatter of this data is typical for the data analysis of this type of system. Since μ_n was controlled to be constant and k_d was found to be a true biokinetic constant, μ ($\mu = \mu_n + k_d$) is constant and the variability observed in Figure 22 is due to the variability in the effluent substrate concentration. The biokinetic constants μ_{max} and K_s can be determined for any probability level desired similar to the concept used to determine the variability in Y_t and k_d.

The S_e probability level desired is determined from Figure 20 for the appropriate specific growth rates and plotted on Figure 22 to determine the desired probability levels of μ_{max} and K_s. As observed in Figure 21 for U, the variability in S_e decreases as μ decreases due to the increased stability of the system at lower growth rates. Thus, the different probability lines all converge to the same intercept indicating the μ_{max} can realistically be treated as a true biokinetic constant, while K_s varies with the population dynamics and should really be treated as a biokinetic coefficient rather than a biokinetic constant.

The maximum specific substrate utilization rate (K), as used in the Lawrence and McCarty design model, can be calculated from the relationship of $\mu_{max} = K \cdot Y_t$ or by making a plot of the reciprocal of the specific substrate utilization rate (U) versus the reciprocal S_e. In this plot, the reciprocal of the Y-axis intercept is equal to K and the slope is equal to K_s/K. A plot of this type is shown for the control data in Figure 23. As pointed out earlier, both U and S_e vary at the same μ_n or SRT. Therefore, the probability lines in Figure 23 require variability analysis of both parameters from the probability plots of Figures 18 and 20.

Since the variability in both U and S_e decrease with decreasing growth rates, the different probability lines all converge toward the same intercept or the same K value. However, since $\mu_{max} = K \cdot Y_t$ and Y_t varies, as shown in Figure 21, μ_{max} and K cannot both be constants. If μ_{max} is treated as a constant in Figure 22 and Y_t varies as shown in Figure 21, K must vary as shown in Figure 23. If K were treated as a constant and Y_t varied, the μ_{max} would vary and the one intercept in Figure 22 would look like the intercepts in Figure 23. Therefore, based on this kinetic analysis as shown in Figure 23, both K and K_s vary with shifts in the population dynamics and should really be treated as biokinetic coefficients rather than biokinetic constants.

In Figure 24, $S_i \cdot U$ is plotted as a function of the effluent substrate concentration for determination of the Eckenfelder modified constant or the Grau constant used in Eckenfleder's modified design model. The slope of the 50 percent line in Figure 24 is equal to the 50 percent K_e'. As with the previous analysis to determine K and K_s, both $S_i \cdot U$ and S_e vary at the same μ_n or SRT, and the lines in Figure 24 require variability analysis of both parameters from the probability plots of Figures 19 and 20. The original Eckenfelder first order substrate utilization rate constant (K_e) can be determined by dividing K_e' by S_i or by plotting U versus S_e and determining the slope. The probability plots of Figures 18 and 20 could then be used to determine the desired probability levels of K_e, if one chose to use Eckenfelder's first order kinetic model. Due to the variability of both U and S_e, both K_e' and K_e vary and should really be treated as biokinetic coefficients rather than biokinetic constants.

All twenty-four single chemical wastewaters and eight combined chemical wastewaters were subjected to the variability analysis for BOD_5, TOC, and COD. As with the control wastewater, both k_d and μ_{max} were treated as biokinetic constants, while K_e', Y_t, K, and K_s were all treated as variabile biokinetic coefficients. The biokinetic constants μ_{max} and k_d in terms of BOD_5, TOC, and COD are given in Table 20 for the single chemical systems and Table 21 for the combined chemical systems. The biokinetic coefficients K_e', Y_t, K, and K_s in terms of BOD_5 are given in Tables 22-25 for the single chemical systems and Tables 26-29 for the combined chemical systems. The biokinetic coefficients K_e', Y_t, K, and K_s in terms of TOC are given in Tables 30-33 for the single chemical systems and Tables 34-37 for the combined chemical systems. Also, the biokinetic coefficients K_e', Y_t, K, and K_s in terms of COD are given in Tables 38-41 for the single chemical systems and Tables 42-45 for the combined chemical systems. The biokinetic coefficients K_e', Y_t, K, and K_s are given for 5, 25, 50, 75, and 95 percent probabilities.

TABLE 20. K_d AND μ_{max} FOR SINGLE CHEMICAL SYSTEMS

Compound	BOD_5		COD		TOC	
	K_d	μ_{max}	K_d	μ_{max}	K_d	μ_{max}
Control	0.09	3.0	0.07	1.9	0.10	4.3
Tetrachloroethane	0.04	1.8	0.06	2.3	0.11	4.0
Nitrobenzene	0.05	3.5	0.05	1.7	0.04	1.9
2,4-Dichlorophenol	0.06	2.0	0.07	1.2	0.06	4.1
Acrylonitrile	0.11	4.7	0.08	1.1	0.06	3.3
Acrolein	0.03	2.2	0.08	1.0	0.05	1.6
1,2-Dichloropropane	0.05	4.0	0.06	1.0	0.04	2.9
Benzene	0.12	1.1	0.14	2.1	0.15	2.0
Methylene Chloride	0.10	1.5	0.10	1.4	0.10	2.2
Ethyl Acetate	0.10	1.3	0.15	1.3	0.15	1.7
1,2-Dichlorobenzene	0.16	1.3	0.22	2.0	0.16	2.6
1,2-Dichloroethane	0.12	1.0	0.12	2.1	0.20	4.0
Phenol	0.18	1.0	0.25	2.0	0.24	2.7
2,4-Dinitrophenol	0.13	4.4	0.15	2.3	0.10	1.6
1,3-Dichlorobenzene	0.07	1.0	0.11	0.9	0.15	2.5
1,1,1-Trichloroethane	0.10	1.8	0.08	2.6	0.10	3.9
Pentachlorophenol	0.06	2.8	0.10	1.9	0.09	2.9
Trichloroethylene	0.15	1.0	0.20	1.5	0.20	2.0
Bis(2-Ethylhexyl) Phthalate	0.27	4.2	0.29	2.9	0.28	3.6
Toluene	0.11	3.2	0.14	2.1	0.13	3.4
Ethylbenzene	0.07	4.0	0.12	2.8	0.10	4.5
Phenanthrine	0.18	1.0	0.21	1.0	0.19	1.6
Chloroform	0.04	2.0	0.07	1.9	0.04	1.8
Carbon Tetrachloride	0.08	1.3	0.10	1.6	0.06	1.8
Naphthalene	0.19	3.3	0.21	2.1	0.23	5.6

TABLE 21. K_d AND μ_{max} FOR COMBINED CHEMICAL SYSTEMS

Combined Systems	BOD5		COD		TOC	
	K_d	μ_{max}	K_d	μ_{max}	K_d	μ_{max}
I	0.10	2.3	0.10	1.9	0.08	2.4
II	0.14	1.0	0.15	2.7	0.13	3.7
III	0.14	4.0	0.16	2.7	0.10	3.6
IV	0.15	1.4	0.25	1.5	0.18	2.3
V	0.13	1.3	0.20	3.7	0.19	4.5
VI	0.16	1.3	0.20	1.5	0.20	3.0
VII	0.15	1.0	0.16	2.1	0.16	2.2
VIII	0.15	2.0	0.20	3.5	0.20	3.3

TABLE 22. K_e' FOR SINGLE CHEMICAL SYSTEMS (BOD_5)

Compound	Percent Probability 5	 25	 50	 75	 95
Control	247	125	71	48	26
Tetrachloroethane	260	149	71	51	28
Nitrobenzene	148	97	77	44	21
2,4-Dichlorophenol	150	90	58	31	15
Acrylonitrile	96	47	31	19	11
Acrolein	48	37	29	20	10
1,2-Dichloropropane	327	193	128	96	45
Benzene	250	150	125	104	71
Methylene Chloride	400	200	133	111	70
Ethyl Acetate	600	330	190	133	64
1,2-Dichlorobenzene	150	92	67	43	15
1,2-Dichloroethane	400	167	100	60	35
Phenol	700	265	160	115	60
2,4-Dinitrophenol	113	73	48	34	20
1,3-Dichlorobenzene	151	93	63	43	29
1,1,1-Trichloroethane	271	134	77	52	21
Pentachlorophenol	228	121	86	60	32
Trichloroethane	179	110	76	58	28
Bis (2-Ethylhexyl) Phthalate	595	300	175	128	83
Toluene	290	159	106	68	44
Ethylbenzene	400	250	160	95	67
Phenanthrene	232	143	103	65	32
Chloroform	278	133	71	42	31
Carbon Tetrachloride	250	90	43	26	18
Naphthalene	112	75	42	27	14

TABLE 23. Y_t FOR SINGLE CHEMICAL SYSTEMS (BOD_5)

Compound	Percent Probability				
	5	25	50	75	95
Control	1.00	0.58	0.46	0.38	0.27
Tetrachloroethane	0.74	0.57	0.46	0.36	0.28
Nitrobenzene	0.92	0.68	0.55	0.43	0.33
2,4-Dichlorophenol	1.50	0.71	0.60	0.45	0.37
Acrylonitrile	1.46	0.86	0.62	0.48	0.37
Acrolein	0.93	0.68	0.54	0.44	0.34
1,2-Dichloropropane	0.81	0.54	0.41	0.35	0.29
Benzene	0.81	0.55	0.53	0.38	0.32
Methylene Chloride	0.94	0.50	0.40	0.35	0.30
Ethyl Acetate	0.89	0.55	0.43	0.33	0.25
1,2-Dichlorobenzene	0.95	0.70	0.58	0.46	0.39
1,2-Dichloroethane	1.20	0.89	0.57	0.50	0.40
Phenol	0.68	0.64	0.60	0.50	0.42
2,4-Dinitrophenol	1.08	0.87	0.73	0.62	0.52
1,3-Dichlorobenzene	0.79	0.65	0.53	0.42	0.33
1,1,1-Trichloroethane	1.00	0.66	0.53	0.43	0.34
Pentachlorophenol	0.65	0.41	0.32	0.25	0.19
Trichloroethylene	0.98	0.76	0.66	0.56	0.46
Bis (2-Ethylhexyl) Phthalate	1.00	0.82	0.70	0.60	0.50
Toluene	1.10	0.79	0.63	0.53	0.41
Ethylbenzene	1.01	0.67	0.50	0.40	0.33
Phenanthrene	1.10	0.75	0.63	0.55	0.46
Chloroform	0.62	0.46	0.39	0.34	0.27
Carbon Tetrachloride	0.87	0.67	0.55	0.50	0.41
Naphthalene	1.25	1.00	0.83	0.71	0.58

TABLE 24. K FOR SINGLE CHEMICAL SYSTEMS (BOD_5)

Compound	Percent Probability				
	5	25	50	75	95
Control	3.0	5.2	6.5	7.9	11.1
Tetrachloroethane	2.4	3.2	3.9	5.0	6.4
Nitrobenzene	3.8	5.1	6.4	8.1	10.6
2,4-Dichlorophenol	1.3	2.8	3.3	4.4	5.4
Acrylonitrile	3.2	5.5	7.6	9.8	12.7
Acrolein	2.4	3.2	4.0	5.0	6.5
1,2-Dichloropropane	4.9	7.4	9.7	11.4	13.8
Benzene	1.4	2.0	2.1	2.9	3.4
Methylene Chloride	1.6	3.0	3.8	4.3	5.0
Ethyl Acetate	1.5	2.4	3.0	3.9	5.2
1,2-Dichlorobenzene	1.4	1.9	2.2	2.8	3.3
1,2-Dichloroethane	0.8	1.1	1.8	2.0	2.5
Phenol	1.5	1.6	1.7	2.0	2.4
2,4-Dinitrophenol	4.1	5.1	6.0	7.1	8.5
1,3-Dichlorobenzene	1.3	1.5	1.9	2.4	3.0
1,1,1-Trichloroethane	1.8	2.7	3.4	4.2	5.3
Pentachlorophenol	4.3	6.8	8.8	11.2	14.7
Trichloroethylene	1.0	1.3	1.5	1.8	2.2
Bis (2-Ethylhexyl) Phthalate	4.2	5.1	6.0	7.0	8.4
Toluene	2.8	4.0	5.1	6.0	7.8
Ethylbenzene	4.0	6.0	8.0	10.0	12.0
Phenanthrene	0.9	1.3	1.6	1.8	2.2
Chloroform	3.2	4.3	5.1	5.9	7.4
Carbon Tetrachloride	1.5	1.9	2.4	2.6	3.2
Naphthalene	2.6	3.3	4.0	4.6	5.7

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TABLE 25. K_S FOR SINGLE CHEMICAL SYSTEMS (BOD_5)

	Percent Probability				
Compound	5	25	50	75	90
Control	45	30	22	16	10
Tetrachloroethane	15	14	12	10	3
Nitrobenzene	41	28	18	17	15
2,4-Dichlorophenol	14	9	8	7	4
Acrylonitrile	51	50	50	45	35
Acrolein	48	46	44	39	25
1,2-Dichloropropane	29	18	19	12	8
Benzene	4	4	3	3	3
Methylene Chloride	6	6	5	4	3
Ethyl Acetate	4	4	4	4	3
1,2-Dichlorobenzene	7	6	4	4	3
1,2-Dichloroethane	2	2	2	2	2
Phenol	3	2	1	1	1
2,4-Dinitrophenol	47	31	27	22	15
1,3-Dichlorobenzene	5	4	3	2	2
1,1,1-Trichloroethane	14	10	8	7	5
Pentachlorophenol	30	27	26	23	15
Trichloroethylene	3	3	3	3	2
Bis (2-Ethylhexyl) Phthalate	15	9	6	5	4
Toluene	16	9	9	8	6
Ethylbenzene	17	13	10	7	3
Phenanthrene	3	3	2	2	2
Chloroform	15	14	12	10	9
Carbon Tetrachloride	9	8	8	5	3
Naphthalene	24	18	17	14	7

TABLE 26. K_e' FOR COMBINED CHEMICAL SYSTEMS (BOD_5)

Combined Systems	Percent Probability				
	5	25	50	75	95
I	280	93	61	41	17
II	111	70	46	29	13
III	175	100	75	57	27
IV	150	96	73	38	23
V	76	42	28	17	9
VI	160	77	45	24	10
VII	188	104	71	35	22
VIII	127	92	71	53	31

TABLE 27. Y_t FOR COMBINED CHEMICAL SYSTEMS (BOD_5)

Combined Systems	Percent Probability				
	5	25	50	75	95
I	1.10	0.60	0.43	0.33	0.27
II	0.89	0.70	0.59	0.51	0.41
III	0.93	0.60	0.47	0.38	0.29
IV	1.20	0.91	0.70	0.54	0.44
V	1.13	0.98	0.84	0.68	0.48
VI	0.79	0.62	0.52	0.44	0.37
VII	1.05	0.86	0.65	0.56	0.47
VIII	0.88	0.65	0.48	0.45	0.41

TABLE 28. K FOR COMBINED CHEMICAL SYSTEMS (BOD_5)

Combined Systems	Percent Probability				
	5	25	50	75	95
I	2.1	3.8	5.3	7.0	8.5
II	1.1	1.4	1.7	2.0	2.4
III	4.3	6.7	8.5	10.5	13.8
IV	1.2	1.5	2.0	2.6	3.2
V	1.2	1.3	1.5	1.9	2.7
VI	1.6	2.1	2.5	3.0	3.5
VII	1.0	1.2	1.5	1.8	2.1
VIII	2.3	3.1	4.2	4.4	4.9

TABLE 29. K_S FOR COMBINED CHEMICAL SYSTEMS (BOD_5)

Combined Systems	Percent Probability				
	5	25	50	75	95
I	22	22	22	19	9
II	8	6	5	3	2
III	27	27	27	23	21
IV	8	6	6	6	5
V	19	12	10	7	5
VI	18	10	7	7	5
VII	3	3	3	3	2
VIII	16	16	16	12	9

TABLE 30. K_e' FOR SINGLE CHEMICAL SYSTEMS (TOC)

Compound	Percent Probability				
	5	25	50	75	95
Control	20.0	8.5	5.5	3.0	1.8
Tetrachloroethane	80.0	32.0	16.0	8.1	2.8
Nitrobenzene	12.0	7.3	4.5	3.0	1.7
2,4-Dichlorophenol	22.5	9.1	6.3	3.2	1.6
Acrylonitrile	12.5	6.8	3.8	2.8	1.7
Acrolein	31.2	11.3	5.3	3.0	1.1
1,2-Dichloropropane	25.0	12.5	7.5	5.0	1.8
Benzene	31.3	10.0	5.6	2.9	1.1
Methylene Chloride	13.6	7.7	4.6	2.8	1.1
Ethyl Acetate	22.9	8.3	7.0	4.2	1.0
1,2-Dichlorobenzene	16.7	8.3	5.7	2.8	1.4
1,2-Dichloroethane	15.0	9.5	5.9	3.5	2.0
Phenol	13.3	7.5	4.5	2.9	1.6
2,4-Dinitrophenol	17.2	10.0	5.6	3.8	2.3
1,3-Dichlorobenzene	41.7	18.7	11.5	9.6	2.5
1,1,1-Trichloroethane	15.6	9.6	5.8	3.4	1.4
Pentachlorophenol	20.0	13.0	8.0	5.0	2.7
Trichloroethylene	25.0	11.1	6.0	4.2	2.1
Bis (2-Ethylhexyl) Phthalate	37.5	14.0	8.1	5.0	1.9
Toluene	20.5	8.4	5.9	3.0	1.0
Ethylbenzene	27.5	13.0	7.0	2.2	1.2
Phenanthrene	6.8	5.4	3.3	2.3	1.6
Chloroform	20.5	11.4	6.3	2.8	1.8
Carbon Tetrachloride	7.0	3.9	3.0	2.1	1.3
Naphthalene	12.5	6.2	4.2	2.2	1.3

TABLE 31. Y_t FOR SINGLE CHEMICAL SYSTEMS (TOC)

Compound	Percent Probability				
	5	25	50	75	95
Control	1.30	1.14	0.86	0.71	1.56
Tetrachloroethane	1.50	0.81	0.60	0.51	0.39
Nitrobenzene	1.24	0.73	0.58	0.38	0.33
2,4-Dichlorophenol	1.64	1.31	1.02	0.91	0.85
Acrylonitrile	1.43	1.00	0.82	0.69	0.57
Acrolein	1.25	0.98	0.78	0.63	0.45
1,2-Dichloropropane	0.77	0.68	0.57	0.41	0.29
Benzene	2.00	1.52	0.98	0.90	0.74
Methylene Chloride	1.60	1.00	0.75	0.57	0.43
Ethyl Acetate	1.65	1.10	0.87	0.75	0.58
1,2-Dichlorobenzene	1.22	0.90	0.66	0.55	0.40
1,2-Dichloroethane	1.56	1.20	1.00	0.77	0.57
Phenol	1.46	1.30	1.14	0.96	0.76
2,4-Dinitrophenol	1.32	0.97	0.78	0.59	0.48
1,3-Dichlorobenzene	1.52	1.03	0.77	0.60	0.47
1,1,1-Trichloroethane	1.38	0.91	0.78	0.63	0.53
Pentachlorophenol	1.33	0.80	0.73	0.54	0.40
Trichloroethylene	1.75	1.20	1.00	0.78	0.67
Bis (2-Ethylhexl) Phthalate	1.88	1.65	1.20	1.00	0.86
Toluene	1.70	1.33	0.86	0.75	0.60
Ethylbenzene	1.40	0.90	0.70	0.52	0.39
Phenanthrene	2.00	1.40	1.20	0.90	0.78
Chloroform	1.06	0.72	0.60	0.52	0.44
Carbon Tetrachloride	1.67	1.12	0.91	0.75	0.61
Naphthalene	2.03	1.58	1.40	1.12	0.94

TABLE 32. K FOR SINGLE CHEMICAL SYSTEMS (TOC)

	Percent Probability				
Compound	5	25	50	75	95
Control	3.3	3.8	5.0	6.0	7.7
Tetrachloroethane	2.7	4.9	6.7	7.8	10.2
Nitrobenzene	1.5	2.6	3.3	5.0	5.8
2,4-Dichlorophenol	2.5	3.1	4.0	4.5	4.8
Acrylonitrile	2.3	3.3	4.0	4.8	5.8
Acrolein	1.3	1.6	2.0	2.5	3.6
1,2-Dichloropropane	3.8	4.3	5.0	7.1	10.0
Benzene	1.0	1.3	2.0	2.2	2.7
Methylene Chloride	1.4	2.2	2.9	3.8	5.1
Ethyl Acetate	1.0	1.5	2.0	2.3	2.9
1,2-Dichlorobenzene	2.1	2.9	4.0	4.7	6.5
1,2-Dichloroethane	2.6	3.3	4.0	5.2	7.0
Phenol	1.8	2.1	2.4	2.8	3.6
2,4-Dinitrophenol	1.2	1.6	2.0	2.7	3.3
1,3-Dichlorobenzene	1.6	2.4	3.3	4.2	5.3
1,1,1-Trichloroethane	2.8	4.3	5.0	6.2	7.4
Pentachlorophenol	2.2	3.6	4.0	5.4	7.3
Trichloroethylene	1.2	1.7	2.0	2.6	3.0
Bis (2-Ethylhexyl) Phthalate	1.9	2.2	3.0	3.6	4.2
Toluene	2.0	2.6	4.0	4.5	5.7
Ethylbenzene	3.2	5.0	6.5	8.6	11.5
Phenanthrene	0.8	1.1	1.3	1.8	2.1
Chloroform	1.7	2.5	2.9	3.5	4.1
Carbon Tetrachloride	1.1	1.6	2.0	2.4	3.0
Naphthalene	2.8	3.5	4.0	5.0	6.0

TABLE 33. K_S FOR SINGLE CHEMICAL SYSTEMS (TOC)

Compound	Percent Probability				
	5	25	50	75	95
Control	215	185	154	140	134
Tetrachloroethane	500	390	200	140	80
Nitrobenzene	200	180	160	130	80
2,4-Dichlorophenol	286	191	160	115	78
Acrylonitrile	230	190	167	115	92
Acrolein	90	50	36	28	20
1,2-Dichloropropane	300	190	150	125	95
Benzene	60	37	32	27	21
Methylene Chloride	105	90	86	70	55
Ethyl Acetate	60	35	32	26	20
1,2-Dichlorobenzene	140	100	89	71	42
1,2-Dichloroethane	195	120	110	92	78
Phenol	120	90	73	50	38
2,4-Dinitrophenol	56	52	49	39	30
1,3-Dichlorobenzene	35	33	31	30	20
1,1,1-Trichloroethane	215	190	165	115	70
Pentachlorophenol	100	95	90	70	55
Trichloroethylene	65	45	37	30	20
Bis (2-Ethylhexyl) Phthalate	90	70	57	50	42
Toluene	95	87	75	55	41
Ethylbenzene	220	177	136	125	111
Phenanthrene	90	75	53	46	40
Chloroform	120	120	94	64	38
Carbon Tetrachloride	76	76	70	68	58
Naphthalene	243	219	164	133	102

TABLE 34. K_e' FOR COMBINED CHEMICAL SYSTEMS (TOC)

Combined Systems	Percent Probability				
	5	25	50	75	95
I	15.0	8.3	5.0	3.2	1.0
II	15.6	7.8	4.7	3.4	2.1
III	13.5	7.3	4.2	2.3	0.9
IV	9.6	5.4	3.1	1.9	1.0
V	18.8	9.1	5.0	3.3	1.4
VI	20.0	8.9	5.2	3.4	1.9
VII	13.0	6.0	3.1	2.2	0.8
VIII	6.0	4.4	3.3	2.5	1.5

TABLE 35. Y_t FOR COMBINED CHEMICAL SYSTEMS (TOC)

Combined Systems	Percent Probability				
	5	25	50	75	95
I	1.33	0.97	0.60	0.40	0.29
II	1.31	1.08	0.93	0.68	0.53
III	2.60	1.60	1.10	0.75	0.56
IV	2.65	1.50	1.14	0.83	0.66
V	2.27	1.90	1.50	1.14	0.88
VI	1.50	1.10	0.90	0.72	0.56
VII	1.75	1.25	0.86	0.75	0.60
VIII	1.65	1.33	1.00	0.80	0.70

TABLE 36. K FOR COMBINED CHEMICAL SYSTEMS (TOC)

Combined Systems	Percent Probability 5	25	50	75	95
I	1.8	2.5	4.0	6.0	8.3
II	2.8	3.4	4.0	5.4	7.0
III	1.4	2.3	3.3	4.8	6.4
IV	0.9	1.5	2.0	2.8	3.5
V	2.0	2.4	3.0	3.9	5.1
VI	2.0	2.7	3.3	4.2	5.4
VII	1.3	1.8	2.5	2.9	3.7
VIII	2.0	2.5	3.3	4.1	4.7

TABLE 37. K_S FOR COMBINED CHEMICAL SYSTEMS (TOC)

Combined Systems	Percent Probability 5	25	50	75	95
I	360	192	185	160	95
II	225	200	135	130	120
III	100	92	90	85	70
IV	90	83	80	74	45
V	135	90	80	75	65
VI	135	100	85	74	64
VII	90	78	70	55	37
VIII	133	125	120	110	100

TABLE 38. K_e' FOR SINGLE CHEMICAL SYSTEMS (COD)

Compound	Percent Probability				
	5	25	50	75	95
Control	40	25	20	13	9
Tetrachloroethane	100	50	32	20	12
Nitrobenzene	50	33	23	14	6
2,4-Dichlorophenol	47	25	17	12	4
Acrylonitrile	33	13	8	6	4
Acrolein	11	8	5	3	2
1,2-Dichloropropane	50	30	20	13	8
Benzene	86	40	27	16	9
Methylene Chloride	80	39	25	14	6
Ethyl Acetate	100	45	29	14	7
1,2-Dichlorobenzene	84	37	20	13	7
1,2-Dichloroethane	91	42	22	15	8
Phenol	84	37	24	21	11
2,4-Dinitrophenol	41	26	17	10	6
1,3-Dichlorobenzene	72	32	20	14	7
1,1,1-Trichloroethane	36	30	22	15	7
Pentachlorophenol	70	35	21	13	9
Trichloroethylene	55	40	30	20	13
Bis (2-Ethylhexyl) Phthalate	67	47	33	24	18
Toluene	80	51	31	22	11
Ethylbenzene	72	38	29	19	8
Phenanthrene	65	36	21	14	6
Chloroform	30	17	13	9	4
Carbon Tetrachloride	26	15	10	7	4
Naphthalene	32	15	12	9	5

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TABLE 39. Y_t FOR SINGLE CHEMICAL SYSTEMS (COD)

Compound	Percent Probability				
	5	25	50	75	95
Control	0.60	0.38	0.28	0.20	0.14
Tetrachloroethane	0.41	0.29	0.23	0.17	0.13
Nitrobenzene	0.46	0.30	0.25	0.20	0.15
2,4-Dichlorophenol	0.46	0.36	0.29	0.22	0.17
Acrylonitrile	0.54	0.43	0.31	0.27	0.23
Acrolein	0.62	0.45	0.35	0.29	0.22
1,2-Dichloropropane	0.65	0.41	0.30	0.22	0.17
Benzene	0.55	0.42	0.32	0.26	0.21
Methylene Chloride	0.50	0.35	0.28	0.22	0.16
Ethyl Acetate	0.60	0.44	0.33	0.27	0.22
1,2-Dichlorobenzene	0.58	0.35	0.30	0.24	0.18
1,2-Dichloroethane	0.51	0.39	0.32	0.24	0.20
Phenol	0.47	0.42	0.40	0.36	0.33
2,4-Dinitrophenol	0.74	0.50	0.35	0.29	0.20
1,3-Dichlorobenzene	0.81	0.49	0.35	0.26	0.20
1,1,1-Trichloroethane	0.43	0.31	0.26	0.21	0.15
Pentachlorophenol	0.41	0.30	0.28	0.24	0.21
Trichloroethylene	0.50	0.40	0.37	0.33	0.25
Bis (2-Ethylhexyl) Phthalate	0.55	0.50	0.44	0.37	0.34
Toluene	0.45	0.36	0.30	0.27	0.23
Ethylbenzene	0.44	0.34	0.28	0.24	0.20
Phenanthrene	0.55	0.44	0.38	0.31	0.27
Chloroform	0.50	0.40	0.29	0.24	0.19
Carbon Tetrachloride	0.68	0.56	0.47	0.38	0.28
Naphthalene	0.72	0.59	0.53	0.48	0.44

TABLE 40. K FOR SINGLE CHEMICAL SYSTEMS (COD)

	Percent Probability				
Compound	5	25	50	75	95
Control	3.2	5.0	6.7	9.5	13.6
Tetrachloroethane	5.6	7.9	10.0	13.5	17.7
Nitrobenzene	3.7	5.7	6.7	8.5	11.3
2,4-Dichlorophenol	2.6	3.3	4.0	5.5	7.1
Acrylonitrile	2.0	2.6	3.5	4.1	4.8
Acrolein	1.6	2.2	2.9	3.4	4.5
1,2-Dichloropropane	1.5	2.4	3.3	4.5	5.9
Benzene	3.8	5.0	6.5	8.0	10.0
Methylene Chloride	2.8	4.0	5.0	6.4	8.7
Ethyl Acetate	2.2	3.0	4.0	4.8	5.9
1,2-Dichlorobenzene	3.4	5.7	6.7	8.3	11.1
1,2-Dichloroethane	4.1	5.4	6.5	8.7	10.5
Phenol	4.2	4.7	5.0	5.6	6.1
2,4-Dinitrophenol	3.1	4.6	6.7	7.9	11.5
1,3-Dichlorobenzene	1.1	1.8	2.5	3.5	4.5
1,1,1-Trichloroethane	6.0	8.4	10.0	12.4	17.3
Pentachlorophenol	4.6	6.3	6.7	7.9	9.0
Trichloroethylene	3.0	3.7	4.0	4.5	6.0
Bis (2-Ethylhexyl) Phthalate	5.3	5.8	6.5	7.8	8.5
Toluene	4.7	5.8	7.0	7.8	9.1
Ethylbenzene	6.4	8.2	10.0	11.7	14.0
Phenanthrene	1.8	2.3	2.5	3.2	3.7
Chloroform	3.8	4.8	6.5	7.9	10.0
Carbon Tetrachloride	2.4	2.9	3.4	4.2	5.7
Naphthalene	2.9	3.6	4.0	4.4	4.8

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TABLE 41. K_s FOR SINGLE CHEMICAL SYSTEMS (COD)

Compound	Percent Probability				
	5	25	50	75	95
Control	140	140	140	135	110
Tetrachloroethane	200	100	90	70	46
Nitrobenzene	250	190	160	150	144
2,4-Dichlorophenol	165	120	85	76	70
Acrylonitrile	200	185	155	126	90
Acrolein	230	225	220	200	150
1,2-Dichloropropane	90	80	73	70	60
Benzene	120	115	110	95	70
Methylene Chloride	140	100	70	55	41
Ethyl Acetate	95	65	60	48	35
1,2-Dichlorobenzene	140	130	120	95	55
1,2-Dichloroethane	175	130	100	80	60
Phenol	140	100	70	55	35
2,4-Dinitrophenol	270	270	270	200	160
1,3-Dichlorobenzene	18	18	17	16	13
1,1,1-Trichloroethane	400	365	320	285	280
Pentachlorophenol	195	185	140	120	70
Trichloroethylene	80	64	50	48	46
Bis (2-Ethylhexyl) Phthalate	115	100	97	84	61
Toluene	177	160	134	120	78
Ethylbenzene	230	174	118	112	85
Phenanthrene	50	41	30	25	22
Chloroform	200	190	185	160	125
Carbon Tetrachloride	137	110	105	93	79
Naphthalene	157	144	110	92	65

TABLE 42. K_e' FOR COMBINED CHEMICAL SYSTEMS (COD)

Combined Systems	Percent Probability 5	25	50	75	95
I	60	32	26	15	9
II	30	20	14	9	5
III	43	23	16	10	3
IV	63	25	13	9	6
V	22	17	10	9	5
VI	46	33	27	19	11
VII	58	39	23	13	9
VIII	25	16	13	10	6

TABLE 43. Y_t FOR COMBINED CHEMICAL SYSTEMS (COD)

Combined Systems	Percent Probability 5	25	50	75	95
I	0.47	0.35	0.28	0.20	0.15
II	0.56	0.48	0.40	0.30	0.20
III	0.88	0.57	0.40	0.31	0.25
IV	0.99	0.81	0.60	0.48	0.40
V	0.84	0.70	0.55	0.43	0.37
VI	0.50	0.35	0.29	0.24	0.37
VII	0.50	0.39	0.31	0.25	0.20
VIII	0.85	0.75	0.69	0.65	0.56

TABLE 44. K FOR COMBINED CHEMICAL SYSTEMS (COD)

Combined Systems	Percent Probability 5	25	50	75	95
I	4.0	5.4	6.7	9.5	12.7
II	4.8	5.6	6.7	9.0	13.5
III	3.1	4.7	6.7	8.7	10.8
IV	1.5	1.9	2.5	3.1	3.8
V	4.4	5.3	6.7	8.6	10.0
VI	3.0	4.3	5.0	6.3	7.5
VII	4.2	5.4	6.7	8.4	10.0
VIII	4.1	4.6	5.0	5.4	6.3

TABLE 45. K_S FOR COMBINED CHEMICAL SYSTEMS (COD)

Combined Systems	Percent Probability 5	25	50	75	95
I	200	180	167	120	106
II	400	350	240	190	150
III	190	178	160	148	110
IV	55	50	45	40	38
V	300	235	220	210	180
VI	115	86	83	76	70
VII	180	155	140	110	77
VIII	205	165	140	120	100

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KINCANNON AND STOVER DESIGN MODEL

The aim of all design models is to provide more accurate predictive equations which are in keeping with the underlying metabolic and biological principles governing the purification process. Most models are developed by writing material balances describing the mass rate of change in substrate and in biomass. Substrate utilization and biomass increase are the two major concerns in the functional design of the bioreactor. Describing mathematically these two functions is where Eckenfelder, McKinney, Lawrence and McCarty, and Gaudy models differ. In addition, Gaudy's model is obtained by writing the mass balance around the bioreactor, whereas, the other three models are obtained by writing mass balances around the entire process.

Figure 25 is a diagram of an activated sludge process including the bioreactor and the mixed liquor separator. If a mass balance for substrate is written around the entire process:

Rate of change of substrate in reactor = Rate of substrate inflow to reactor − Rate of substrate outflow from reactor − Rate of substrate utilization

$$\left(\frac{dS}{dt}\right)_R V = FS_i - FS_e - \left(\frac{dS}{dt}\right)_g V \qquad \text{(Eq. 1)}$$

For steady state conditions $\left(\frac{dS}{dt}\right)_R = 0$. Therefore

$$\left(\frac{dS}{dt}\right)_g V = FS_i - FS_e \qquad \text{(Eq. 2)}$$

The various models differ by the assumption for $(dS/dt)_g$:

Eckenfelder

First Order $$\left(\frac{dS}{dt}\right)_g = K_e X S_e \qquad \text{(Eq. 3)}$$

Second Order $$\left(\frac{dS}{dt}\right)_g = \frac{K_e' X S_e}{S_i} \qquad \text{(Eq. 4)}$$

McKinney

$$\left(\frac{dS}{dt}\right)_g = K_m S_e \qquad \text{(Eq. 5)}$$

Lawrence and McCarty

$$\left(\frac{dS}{dt}\right)_g = \frac{K X S_e}{K_s + S_e} \qquad \text{(Eq. 6)}$$

Gaudy

$$\left(\frac{dS}{dt}\right)_g = \frac{\mu_{max} X S_e}{Y_t(K_s + S_e)} \qquad \text{(Eq. 7)}$$

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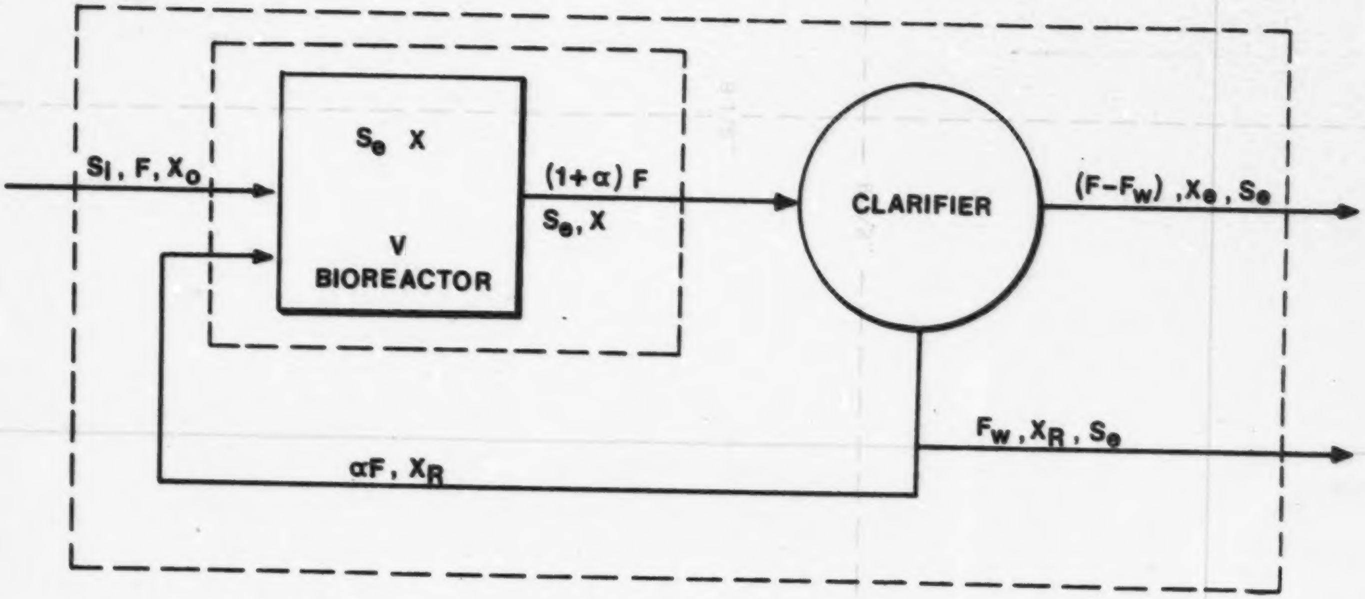
S_I, F, X_o
S_e X
V
BIOREACTOR
(1+α) F
S_e, X
CLARIFIER
$(F-F_W)$, X_e, S_e
F_W, X_R, S_e
αF, X_R

Figure 25. Flow diagram, activated sludge process showing notation and mass balance envelopes.

It was seen earlier in this report that only μ_{max} and K_d were true constants and that K_e', Y_t, K, and K_s showed a great amount of variability. The design model developed by Kincannon and Stover eliminates this variability. This is accomplished by assuming the following relationship:

$$\left(\frac{dS}{dt}\right)_g = \frac{U_{max}\ X\ \dfrac{FS_i}{XV}}{K_B + \dfrac{FS_i}{XV}} \qquad \text{(Eq. 8)}$$

where:

U_{max} = maximum substrate utilization rate

K_B = substrate loading at which the rate of substrate utilization is one-half the maximum rate.

This relationship assumes that substrate utilization is a function of the mass loading per mass of microorganisms rather than the substrate concentration. The term FS_i/xv is the well known F/M ratio. This relationship is shown graphically in Figure 26. One may reason that the relationship is actually first order. This is especially true when the F/M values are below 2/lbs BOD_5/lb solids · day. Most activated sludge systems are operated at F/M values below 1.0. If data at F/M values of 2.0 or less are used then the plot may appear to be first order. However, if the data contains F/M values equal to or greater than 5.0 then the data will plot as a "Monod" type relationship. Thus, equation 8 would describe the relationship in Figure 26 rather than being described as first order.

The biokinetic constants U_{max} and K_B can be determined by linearizing equation 8:

$$\frac{1}{dS/dt\ X} = \frac{K_B}{U_{max}}\ \frac{1}{FS_i/XV} + \frac{1}{U_{max}} \qquad \text{(Eq. 9)}$$

and plotting $1/dS/dt\ X$ vs $1/FS_i/XV$. The y-axis intercept is equal to $1/U_{max}$ and the slope of the line is equal to K_B/U_{max}. This is illustrated for the Kraft Paper Mill wastewater in Figure 27.

The model is developed by substituting equation 8 into equation 2.

$$\frac{U_{max}\ X\ (FS_i/XV)\ V}{K_B + FS_i/XV} = FS_i - FS_e \qquad \text{(Eq. 10)}$$

Solving for S_e gives

$$S_e = S_i - \frac{U_{max}\ S_i}{K_B + FS_i/XV} \qquad \text{(Eq. 11)}$$

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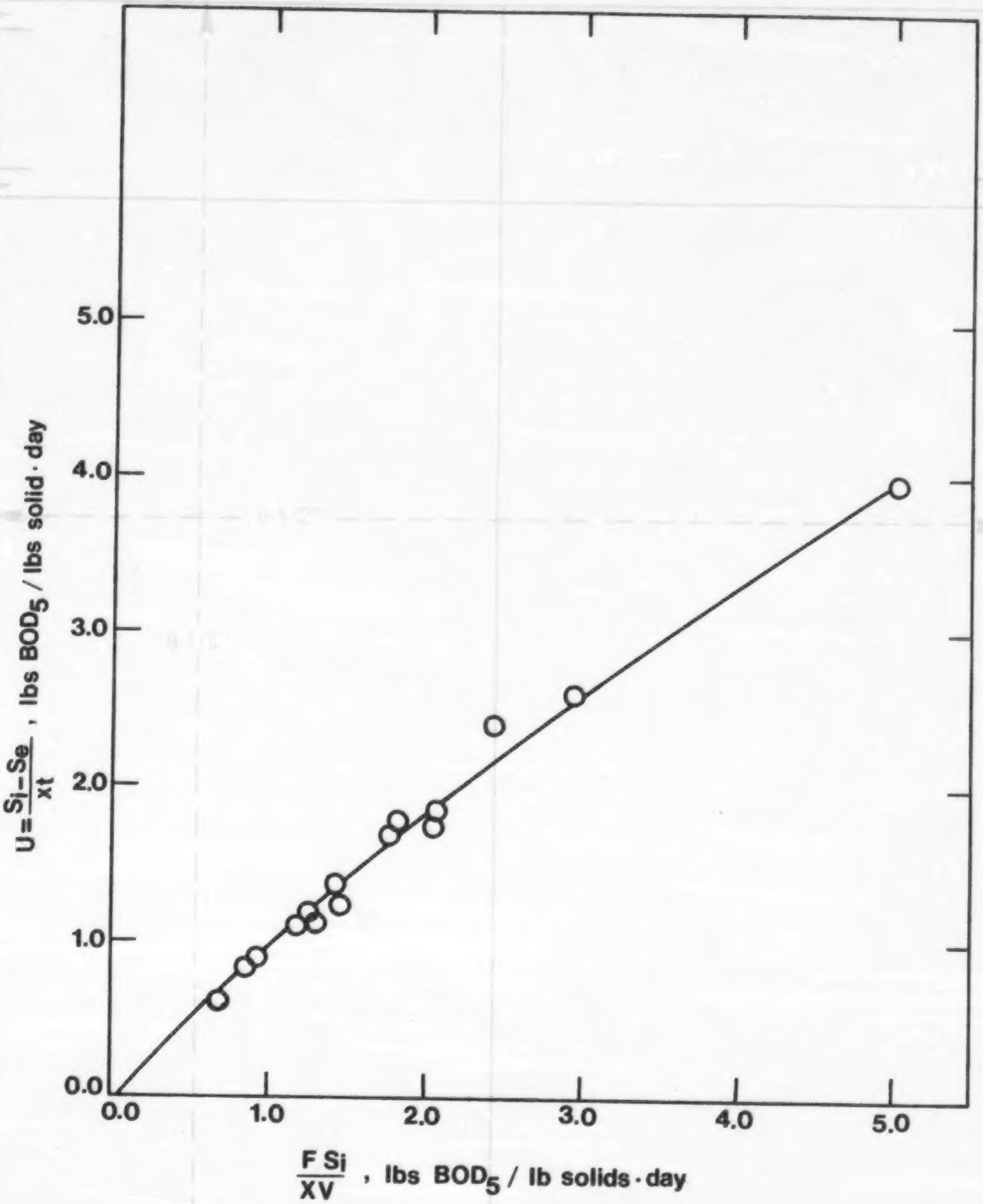

Figure 26. Relationship between specific substrate utilization rate and specific substrate loading for a Kraft Paper Mill wastewater.

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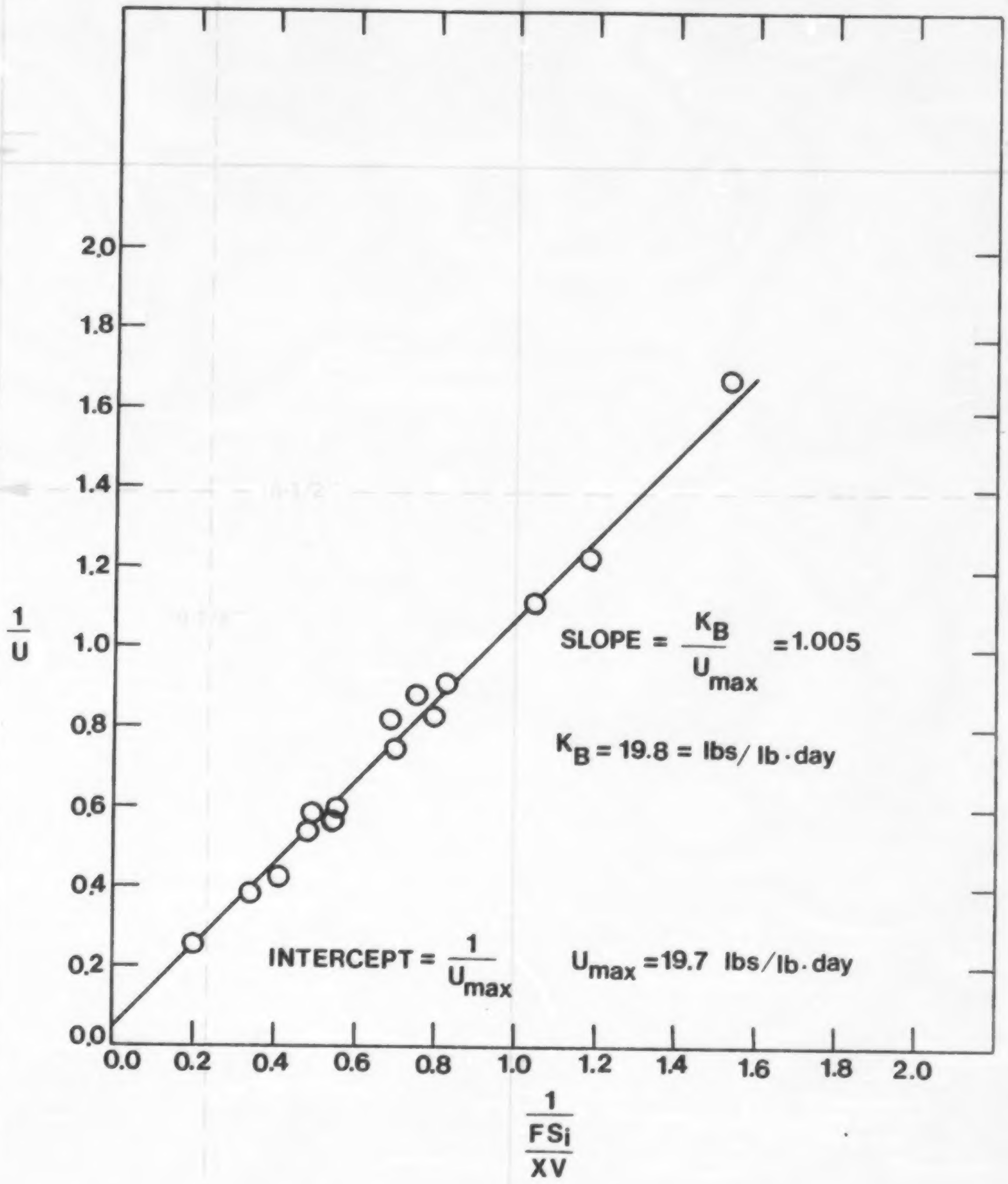

Figure 27. Graphical determination of U_{max} and K_B.

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or solving fof XV gives

$$XV = \frac{FS_i}{\dfrac{U_{max}\ S_i}{S_i - S_e} - K_B} \qquad \text{(Eq. 12)}$$

and the effluent BOD_5 or aeration tank volume can be calculated for any given situation.

The biokinetic constants U_{max} and K_B were determined for the twenty-four single chemical systems and the eight combined chemical systems. A plot of $S_i - S_e/Xt$ vs FS_i/XV for 2,4 dichlorophenol is shown in Figure 28. It is seen that the values for FS_i/XV are below 2.0 lbs BOD_5/lbs solids · days. This does not provide for a well defined curve. However, it must be remembered that the experimental plan was not developed for this design approach. If Figure 28 was to be used without prior studies showing that the data should follow a "Monod" type relationship then one might reason that the relationship is first order. However, Figure 26 and other data has shown that the relationship is not first order. Figure 28 is typical for all systems studied. The biokinetic constants U_{max} and K_B were determined by plotting $1/U$ vs $1/FS_i/XV$ as shown in Figure 29. Linear regression analyses were conducted for all systems and the resultant values for U_{max} and K_B are given in Table 46. It was found that $1/U$ and $1/FS_i/XV$ had to be carried at three decimal places. This was due to the high treatment efficiencies achieved by the systems. At these high treatment efficiencies, the difference between U and FS_i/XV were in the third decimal place.

FATE OF SPECIFIC CHEMICALS

Nonbiological systems were operated to determine the strippability of each specific chemical. In these studies, the reactor and settling compartment were filled with distilled water. The feed tank contained the wastewater. The wastewater was pumped to the reactor and the level of TOC in the reactor was observed as a function of time. Dilute-in curves for eight specific chemicals are shown in Figure 30. A variety of dilute-in curves are shown. Phenol follows the theoretical dilute-in, while the base mix is approximately eighty-five percent, ethyl acetate twenty percent, and 1,2-dichloroethane ten percent of the theoretical. The chemicals 1,2-dichlorobenzene, methylene chloride, benzene, and 1,2-dichloropropane showed no dilute-in. When the wastewater had been completely diluted –in, influent, effluent, and off-gas samples were collected for specific chemical analyses. The percent stripped of each chemical was determined and is given in Table 47. The chemicals studied provided various levels of stripping.

It was of interest to determine the removal mechanism for each specific chemical during biological treatment by the activated sludge process. Stripping was determined by measuring the off-gases. Sorption was determined by 24-hour continuous solvent extraction or purging sludge samples. Biological degradation was assumed to account for the rest of the removal. The percent

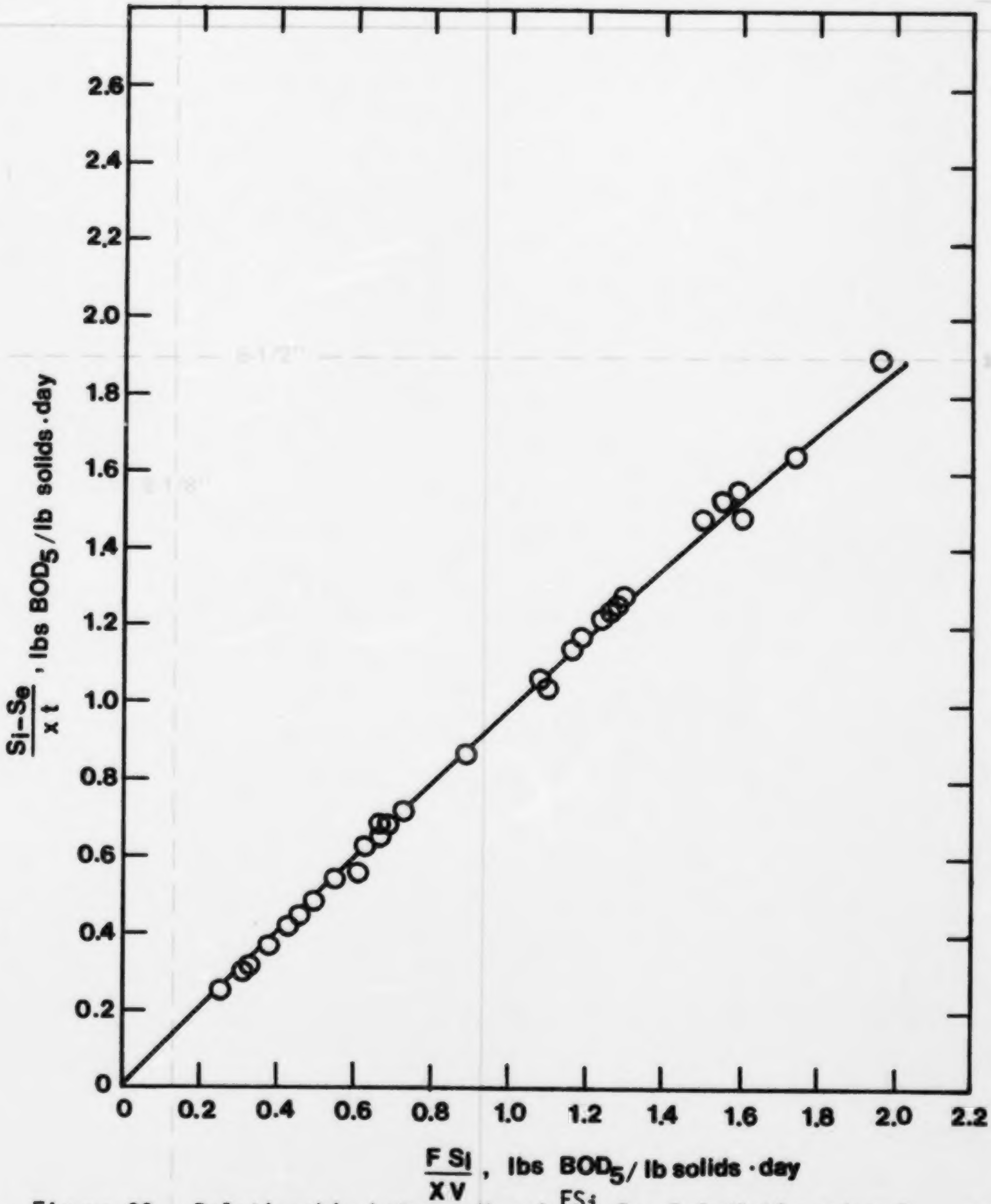

Figure 28. Relationship between U and $\frac{FS_i}{XV}$ for 2,4-dichlorophenol.

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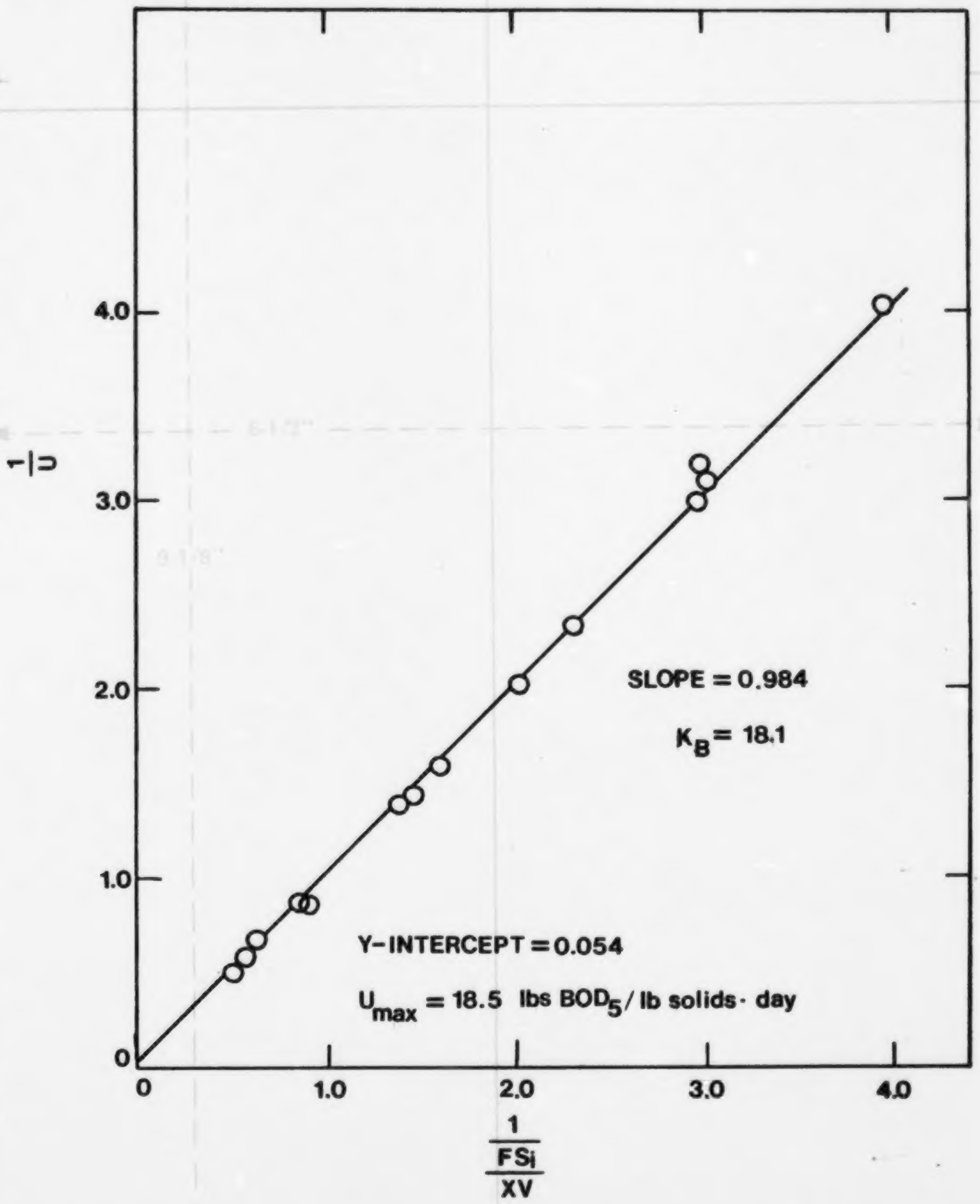

Figure 29. Determination of U_{max} and K_B for 2,4-dichlorophenol.

TABLE 46. BIOKINETIC CONSTANTS FOR KINCANNON AND STOVER'S DESIGN MODEL (BOD_5)

Chemical	U_{max}	K_B
Control	134.7	136.1
Tetrachloroethane	102.2	102.9
Nitrobenzene	43.2	43.0
2,4 Dichlorophenol	18.5	18.1
Combined I	110.0	111.3
Acrylonitrile	46.2	46.4
Acrolein	56.3	57.0
1,2 Dichloropropane	244.4	246.1
Combined II	40.7	40.6
Benzene	100.0	100.8
Methylene chloride	232.9	235.5
Ethyl acetate	38.5	37.9
Combined III	172.7	174.1
1,2 Dichlorobenzene	47.0	46.8
1,2 Dichloroethane	33.1	32.8
Phenol	276.2	279.0
Combined IV	18.0	17.5
2,4 Dinitrophenol	112.5	113.4
1,3 Dichlorobenzene	9.0	8.2
1,1,1 Trichloroethane	45.0	45.0
Combined V	8.5	8.2
Pentachlorophenol	38.9	38.0
Trichloroethylene	17.4	16.9
Bis (2-ethylhexyl) phthalate	111.0	111.0
Combined VI	50.0	50.0
Toluene	70.8	71.0
Ethylbenzene	184.8	184.8
Phenanthrene	250.8	251.8
Combined VII	72.0	71.9
Chloroform	80.0	79.8
Carbon tetrachloride	85.6	86.1
Naphthalene	110.0	111.2
Combined VIII	105.2	106.0

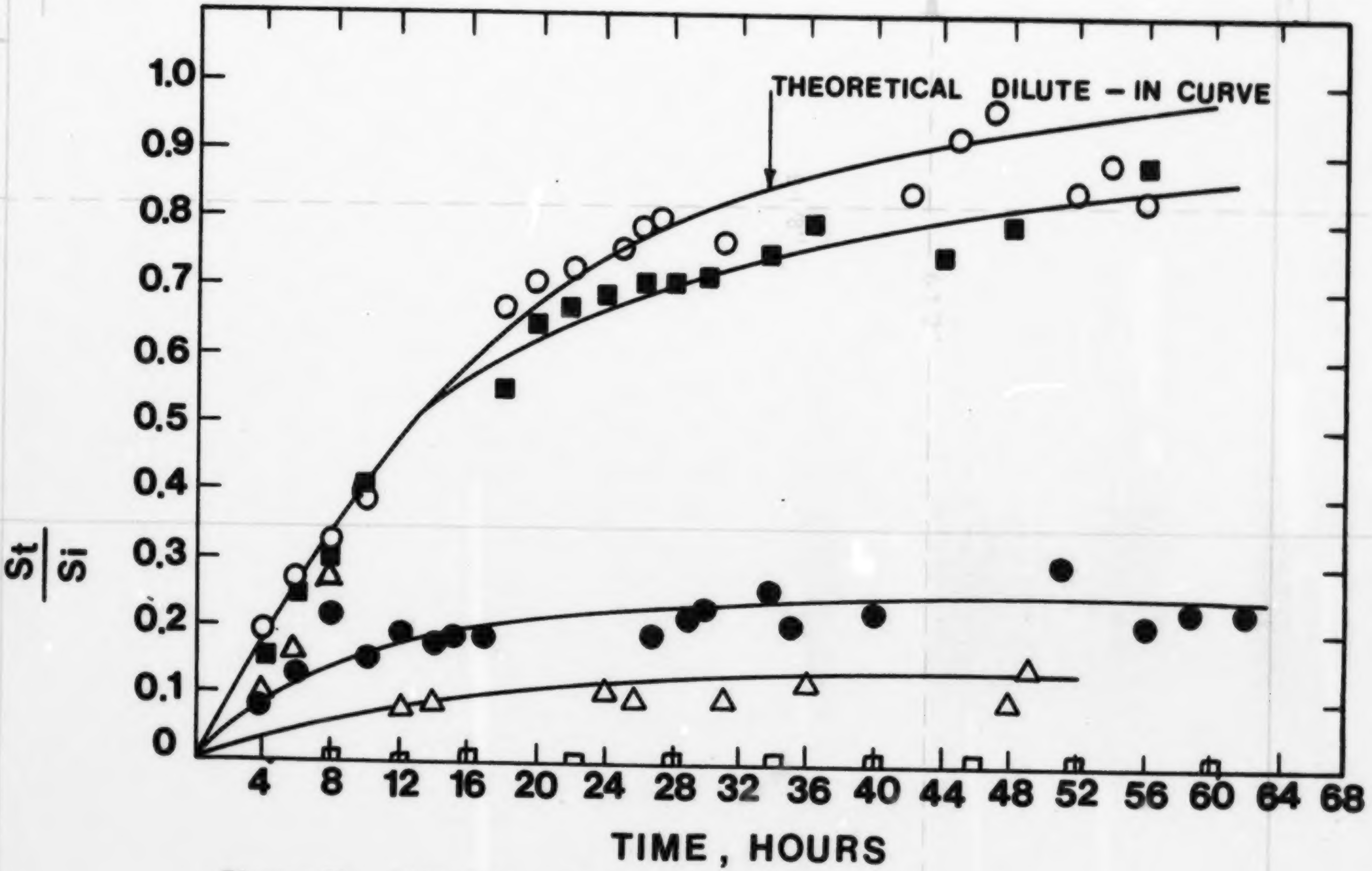

Figure 30. Dilute-in curves for test compounds.

○ phenol; ■ base mix; ● ethyl acetate; △ 1,2-dichloroethane;

□ 1,2-dichlorobenzene, methylene chloride, benzene, 1,2-dichloropropane.

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TABLE 47. STRIPPING OF CHEMICALS IN NONBIOLOGICAL SYSTEMS

CHEMICAL	Percent Stripped in Nonbiological Systems
Nitrogen Compounds	
Acrylonitrile	76
Phenols	
Phenol	0
2,4-Dinitrophenol	0
2,4-Dichlorophenol	*
Pentachlorophenol	0
Aromatics	
1,2-Dichlorobenzene	85
1,3-Dichlorobenzene	98
Nitrobenzene	*
Benzene	99
Toluene	99
Ethylbenzene	99
Halogenated Hydrocarbons	
Methylene Chloride	99
1,2-Dichloroethane	96
1,1,1-Trichloroethane	97
1,1,2,2-Tetrachloroethane	95
1,2-Dichloropropane	99
Trichloroethylene	99^{+}
Chloroform	*
Carbon Tetrachloride	*
Oxygenated Compounds	
Acrolein	62
Polynuclear Aromatics	
Phenanthrene	*
Naphthalene	*
Phthalates	
Bis(2-Ethylhexyl)	*
Other	
Ethyl Acetate	82
Base Mix	15

* No data available.

removals achieved by stripping, sorption, and biodegradation for both the single chemical systems and the combined chemical systems are shown in Table 48. It is seen that the removal mechanisms varied from complete stripping to complete biodegradation with some chemicals being removed by both biodegradation and stripping. Sorption was not an important removal mechanism for these chemicals. It is also seen that similar removal efficiencies were obtained in both the single and combined systems.

PREDICTION CAPABILITIES

Biokinetic Constants

The primary objective of this study was to determine the biokinetic parameters to use in process modeling for predicting effluent quality and design configurations of activated sludge process treating waste streams from chemical and plastics manufacture. To accomplish this, biokinetic constants for the design models after Eckenfelder, Lawrence and McCarty, and Gaudy have been determined. In addition, a new design model (Kincannon and Stover) has been developed and it's required biokinetic constants have been determined. It is of interest to compare the design values obtained by each design model and their respective biokinetic constants. Therefore, the aeration tank volume was calculated, using each design model, for a given situation. The 50 percentile biokinetic constants were used for Eckenfelder, Lawrence and McCarty and Gaudy's design models. These calculated aeration tank volumes are shown in Table 49. McKinney's design model would give the same answer as Eckenfelder. It is seen that all models provided similar volume with just slight variations. Thus, all four models can be used with equal confidence.

Another objective of this study was to determine whether or not biokinetic constants from single chemical systems could be combined to give a biokinetic constant that would be representative of the combined chemical system. To accomplish this, combined chemical systems containing three chemicals used in the single chemical systems were studied. The combined systems predicted biokinetic constants are given in Tables 50, 51, and 52. The predicted values were made by averaging the biokinetic constants obtained in the single studies and by a weighted average based upon the amount present in the single unit. Using Group I as an example, the predicted value of K_e' would be:

average method-

$$\text{combined } K_e' = \frac{71 + 77 + 58}{3} = 69 \text{ days}^{-1}$$

weighted average method -

$$\text{combined } K_e' = \frac{52}{201}(71) + \frac{37.5}{100}(77) + \frac{24.1}{75}(58) = 66 \text{ days}^{-1}$$

TABLE 48. REMOVAL MECHANISMS OF TOXIC ORGANICS

Compound	Percent Treatment Achieved					
	Single Units			Combined Units		
	Strip.*	Sorption	Biol.**	Strip.	Sorption	Biol.
Nitrogen Compounds						
Acrylonitrile			99.9			90.0
Phenols						
Phenol			99.9			99.9
2,4-DNP			99.3			99.2
2,4-DCP			95.2			77.1
PCP		0.58	97.3			97.8
Aromatics						
1,2-DCB	21.7		78.2			99.9
1,3-DCB	-	-	-	-	-	-
Nitrobenzene			97.8			33.8
Benzene	2.0		97.9	2.0		97.2
Toluene	5.1	0.02	94.9	6.2		93.7
Ethylbenzene	5.2	0.19	94.6	7.5		92.4
Halogenated Hydrocarbons						
Methylene Chloride	8.0		91.7	2.0		97.2
1,2-DCE	99.5	0.50		75.0		25.0
1,1,1-TCE	100.0			99.7	0.30	
1,1,2,2-TCE	93.5			96.2		
1,2-DCP	99.9			99.5		
TCE	65.1	0.83	33.8	69.7		30.1
Chloroform	19.0	1.19	78.7	15.0	1.36	82.8
Carbon Tetrachloride	33.0	1.38	64.9	28.0	0.03	71.7
Oxygenated Compounds						
Acrolein			99.9			90.0
Polynuclear Aromatics						
Phenanthrene			98.2			94.7
Naphthalene			98.6			78.6
Phthalates						
Bis(2-Ethylhexyl)			76.9			85.7
Other						
Ethyl Acetate	1.0		98.8			98.9

* Strip. = Stripping
** Biol. = Biological

TABLE 49. AERATION TANK VOLUMES CALCULATED BY VARIOUS DESIGN MODELS

Design conditions

S_i = 220 mg/ℓ BOD_5

S_e = 4 mg/ℓ

50 percentile biokinetics used

Calculate volume in million gallons

X = 1000 mg/ℓ

F = 100 mg/ℓ

System	Eckenfelder Second Order	Lawrence and McCarty	Gaudy	Kincannon and Stover
Control	1.67	2.16	2.10	2.01
Tetrachloroethane	1.67	2.22	2.14	1.84
Nitrobenzene	1.54	1.86	1.84	2.20
2,4 dichlorophenol	2.05	1.96	1.91	2.96
Combined I	1.95	2.65	2.56	2.98
Acrylonitrile	3.83	3.84	3.76	3.36
Acrolein	4.10	6.48	6.20	6.42
1,2 dichloropropane	0.93	1.28	1.25	0.78
Combined II	2.58	2.86	2.81	2.58
Benzene	0.95	1.80	1.78	2.09
Methylene chloride	0.89	1.28	1.29	1.28
Ethyl acetate	0.63	1.44	1.41	1.68
Combined III	1.58	1.97	1.95	1.22
1,2 dichlorobenzene	1.77	1.96	1.88	2.05
1,2 dichloroethane	1.19	1.80	1.79	2.41
Phenol	0.74	1.59	1.57	0.95
Combined IV	1.63	2.70	2.60	2.64
2,4 dinitrophenol	2.48	2.79	2.70	1.86
1,3 dichlorobenzene	1.89	1.99	1.95	2.28
1,1,1 trichloroethane	1.54	1.91	1.86	2.64
Combined V	4.24	5.04	4.79	4.81
Pentachlorophenol	1.38	1.84	1.82	1.36
Trichloroethylene	1.56	2.52	2.47	2.68
Bis(2-ethylhexyl) phthalate	0.68	0.90	0.89	1.07
Combined VI	2.64	2.38	2.36	2.38
Toluene	1.12	1.38	1.35	1.98
Ethylbenzene	0.74	0.95	0.94	0.64
Phenanthrene	1.15	2.03	2.03	0.60
Combined VII	1.67	2.52	2.44	1.53
Chloroform	1.67	1.69	1.67	1.31
Carbon tetrachloride	2.76	2.70	2.67	2.03
Naphthalene	2.83	2.84	2.84	2.62
Combined VIII	1.67	2.57	2.59	1.92

TABLE 50. PREDICTED VERSUS MEASURED BIOKINETIC CONSTANTS IN COMBINED UNITS (BOD_5)

Parameter		I	II	III	IV	V	VI	VII	VIII
K_d	measured	0.10	0.14	0.14	0.15	0.13	0.16	0.15	0.15
	average	0.05	0.06	0.11	0.15	0.10	0.16	0.12	0.10
	weighted avg.	0.05	0.05	0.10	0.12	0.11	0.40	0.09	0.11
Y_t	measured	0.43	0.59	0.47	0.70	0.84	0.52	0.65	0.48
	average	0.54	0.52	0.45	0.58	0.60	0.56	0.59	0.59
	weighted avg.	0.52	0.51	0.44	0.43	0.66	1.30	0.55	0.63
K_e'	measured	61.0	46.0	75.0	73.0	28.0	45.0	71.0	71.0
	average	69.0	63.0	150.0	109.0	63.0	112.0	123.0	52.0
	weighted avg.	66.0	55.0	137.0	93.0	74.0	226.0	116.0	58.0
μ_m	measured	2.3	1.0	4.0	1.4	1.3	1.3	1.0	2.0
	average	2.4	3.6	1.3	1.1	2.4	2.7	2.7	2.2
	weighted avg.	2.4	3.1	1.2	0.8	2.5	6.2	2.5	2.4
K	measured	5.3	1.7	8.5	2.0	1.5	2.5	1.5	4.2
	average	4.5	7.1	3.0	1.9	3.8	5.4	4.9	3.8
	weighted avg.	4.5	6.1	2.7	1.3	4.1	11.0	4.5	4.3
K_s	measured	22.0	5.0	27.0	6.0	10.0	7.0	3.0	16.0
	average	13.0	39.0	4.0	2.0	13.0	12.0	7.0	12.0
	weighted avg.	12.0	38.0	4.0	1.3	13.0	20.0	6.0	14.0
U_{max}	measured	110.0	40.7	172.7	18.0	8.5	50.0	72.0	105.2
	average	54.6	115.6	90.5	118.8	55.5	55.8	168.8	91.9
	weighted avg.	48.8	102.1	112.2	117.6	62.7	179.8	164.2	100.9
K_B	measured	111.3	40.6	174.1	17.5	8.2	50.0	71.9	106.0
	average	54.7	116.5	124.7	119.5	55.5	55.3	169.2	92.4
	weighted avg.	48.8	102.9	112.1	118.4	62.8	179.6	164.1	101.4

TABLE 51. PREDICTED VERSUS MEASURED BIOKINETIC CONSTANTS IN COMBINED UNITS (TOC)

Parameter		I	II	III	IV	V	VI	VII	VIII
K_d	measured	0.08	0.13	0.10	0.18	0.19	0.20	0.16	0.20
	average	0.07	0.05	0.13	0.20	0.12	0.19	0.14	0.11
	weighted avg.	0.06	0.05	0.13	0.16	0.13	0.56	0.13	0.11
Y_t	measured	0.60	0.93	1.10	1.14	1.50	0.90	0.86	1.00
	average	0.73	0.72	0.87	0.94	0.78	0.98	0.92	0.97
	weighted avg.	0.70	0.70	0.81	0.75	0.88	2.65	0.87	1.05
K_e'	measured	5.0	4.7	4.2	3.1	5.0	5.2	3.1	3.3
	average	8.9	5.5	5.7	5.4	7.6	7.4	5.4	4.5
	weighted avg.	7.9	5.4	5.5	3.8	8.1	18.8	5.0	5.0
μ_m	measured	2.4	3.7	3.6	2.3	4.5	3.0	2.2	3.3
	average	3.3	2.6	2.0	3.1	2.7	2.8	3.2	2.1
	weighted avg.	3.1	2.2	1.8	2.3	3.2	7.6	2.9	3.3
K	measured	4.0	4.0	3.3	2.0	3.0	3.3	2.5	3.3
	average	4.7	3.7	2.3	3.5	3.4	3.0	3.9	3.0
	weighted avg.	4.3	3.1	2.2	2.4	4.2	5.8	3.6	3.2
K_s	measured	185.0	135.0	90.0	80.0	80.0	85.0	70.0	120.0
	average	173.3	117.7	50.0	90.7	81.7	61.3	88.0	109.2
	weighted avg.	164.0	90.4	46.8	64.8	109.3	127.7	82.5	118.1

TABLE 52. PREDICTED VERSUS MEASURED BIOKINETIC CONSTANTS IN COMBINED UNITS (COD)

Parameter		I	II	III	IV	V	VI	VII	VIII
K_d	measured	0.10	0.15	0.16	0.25	0.20	0.20	0.16	0.20
	average	0.06	0.07	0.13	0.20	0.11	0.20	0.16	0.13
	weighted avg.	0.06	0.07	0.12	0.15	0.12	0.58	0.15	0.14
Y_t	measured	0.28	0.40	0.40	0.60	0.55	0.29	0.31	0.69
	average	0.26	0.32	0.31	0.34	0.32	0.36	0.32	0.43
	weighted avg.	0.25	0.32	0.29	0.26	0.35	0.98	0.30	0.47
K_e'	measured	26.0	14.0	16.0	13.0	10.0	27.0	23.0	13.0
	average	24.0	11.0	27.0	22.0	19.7	28.0	27.0	11.7
	weighted avg.	22.5	7.48	25.5	16.8	22.6	74.91	25.1	12.9
μm	measured	1.9	2.7	2.7	1.5	3.7	1.5	2.1	3.5
	average	1.7	1.0	1.6	2.0	1.9	2.1	2.0	1.9
	weighted avg.	1.6	1.0	1.5	1.5	2.3	5.8	1.8	2.1
K	measured	6.7	6.7	6.7	2.5	6.7	5.0	6.7	5.0
	average	6.9	3.2	5.2	6.1	6.4	5.7	6.5	4.6
	weighted avg.	6.4	3.0	4.7	4.3	8.0	14.6	6.0	5.2
K_s	measured	167.0	240.0	160.0	45.0	220.0	83.0	140.0	140.0
	average	111.7	149.3	80.0	96.7	202.3	95.7	94.0	133.3
	weighted avg.	111.4	160.0	72.0	65.0	257.2	229.9	85.5	149.4

where:

52 = tetrachloroethane concentration in combined unit
201 = tetrachloroethane concentration in single unit
71 = K_e' for tetrachloroethane single unit
37.5 = nitrobenzene concentration in combined unit
100 = nitrobenzene concentration in single unit
77 = K_e' for nitrobenzene single unit
24.1 = 2,4 dichlorophenol concentration in combined unit
75 = 2,4 dichlorophenol concentration in single unit
58 = K_e' for 2,4 dichlorophenol single unit

When comparing the predicted values with the measured values, it is seen that one method did not predict any better than the other method. In some cases the predictions were fairly good, but overall the predictions were not satisfactory. It is important to recognize that the removal mechanism was not taken into account when determining the biokinetic constants, since BOD_5, TOC, and COD removal was total removal. The actual removal mechanism may have exerted some effect on the biokinetic constants, and it may be important to separate the removal according to mechanism. Tables 53 and 54 give the concentration of BOD_5, TOC, and COD stripped from the single and combined chemical systems. Table 53 also gives the concentration of specific chemical stripped. The concentration of BOD_5, TOC, and COD stripped was determined by using the mg BOD_5, TOC, or COD per mg chemical which is given in Table 3. Sorption was not considered because of the low concentrations that were removed by this mechanism.

The kinetic models used in this study were developed by using a mass balance that includes only biological removal of substrate. Where stripping and/or adsorption become important considerations, a more logical substrate mass balance would be:

$$\begin{array}{ccccccccccc} \text{change of mass in reactor} & = & \text{mass entering reactor} & - & \text{mass leaving reactor in effluent} & - & \text{mass consumed biologically} & - & \text{mass stripped} & - & \text{mass adsorbed} \\ \left(\frac{dS}{dt}\right)_R V & = & FS_i & - & FS_e & - & \left(\frac{dS}{dt}\right)_G V & - & \left(\frac{dS}{dt}\right)_S V & - & \left(\frac{dS}{dt}\right)_A V \end{array}$$

where:

$\left(\frac{dS}{dt}\right)_R$ = 0, steady state conditions

$\left(\frac{dS}{dt}\right)_G$ would depend upon the choice of model

$\left(\frac{dS}{dt}\right)_S = K_L (S_e - S_a)$

K_L = stripping constant, day^{-1}
S_e = effluent concentration
S_a = concentration of strippable chemical in air above reactor

$\left(\frac{dS}{dt}\right)_A$ needs development. Based upon sludge analysis will assume zero for these studies.

TABLE 53. BOD_5, TOC, AND COD STRIPPED FROM SINGLE CHEMICAL SYSTEMS

Compound	Specific Compound		BOD_5		TOC		COD	
	Initial	Stripped	Initial	Stripped	Initial	Stripped	Initial	Stripped
Benzene	153	3.1	212	1.7	132	2.8	441	9.5
Toluene	59	3.0	180	3.0	129	2.1	416	7.5
Ethylbenzene	60	3.1	236	2.3	143	1.5	520	5.0
Methylene Chloride	180	14.4	287	-	170	2.0	480	8.1
1,2-Dichloroethane	258	256.7	201	0	187	61.6	460	249.0
1,1,1-Trichloroethane	118	117.0	244	0	183	14.0	530	32.8
1,1,2,2-Tetrachloroethane	201	188.0	244	0	224	26.3	496	90.2
1,2-Dichloropropane	182	181.8	247	0	199	58.2	480	230.9
Trichloroethylene	95	61.8	295	0	179	6.2	530	17.3
Chloroform	35	6.6	240	0.4	155	0.7	363	0.9
Carbon Tetrachloride	18	5.9	257	-	162	0.5	387	1.2
Ethyl Acetate	167	1.7	259	1.3	145	0.7	450	3.1

All concentrations are in mg/ℓ.

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TABLE 54. BOD_5, TOC, AND COD STRIPPED FROM COMBINED CHEMICAL SYSTEMS

Combined Systems	BOD_5		TOC		COD	
	Initial	Stripped	Initial	Stripped	Initial	Stripped
I	314	0	246	7.3	574	25.0
II	279	0	197	15.4	565	61.0
III	248	0.4	133	0.9	400	3.0
IV	268	0	176	11.3	454	45.8
V	227	0	143	7.2	429	16.7
VI	270	0	169	4.6	574	12.9
VII	217	1.1	147	1.4	470	4.9
VIII	317	0.1	170	0.4	409	0.7

All concentrations are in mg/ℓ.

Substrate mass balance expressions for each design method becomes:

Eckenfelder

$$\left(\frac{dS}{dt}\right)_G = \frac{K_e' \, X \, S_e}{S_i}$$

and

$$0 = FS_i - FS_e - \frac{K_e' \, X \, S_e V}{S_i} - K_L(S_e - S_a) V$$

$$K_e' = \frac{S_i(S_i - S_e)}{Xt \, S_e} - \frac{S_i K_L \, (S_e - S_a)}{X \, S_e}$$

Lawrence and McMarty

$$\left(\frac{dS}{dt}\right)_G = \frac{K \, X \, S_e}{K_s + S_e}$$

$$0 = FS_i - FS_e - \frac{K \, X \, S_e \, V}{K_s + S_e} - K_L \, (S_e - S_a) \, V$$

$$\frac{S_i - S_e}{Xt} - \frac{K_L \, (S_e - S_a)}{X} = \frac{K \, S_e}{K_s + S_e}$$

or

$$\frac{1}{\frac{S_i - S_e}{Xt} - \frac{K_L \, (S_e - S_a)}{X}} = \frac{1}{S_e} \, \frac{K_s}{K} + \frac{1}{K}$$

Gaudy

$$\left(\frac{dS}{dt}\right)_G = \left(\frac{\mu_{max} \; S_e}{K_s + S_e}\right) \frac{X}{Y_t}$$

$$0 = FS_i - FS_e - \left(\frac{\mu_{max} \; S_e}{K_s + S_e}\right) \frac{XV}{Y_t} - K_L \, (S_e - S_a) \, V$$

$$Y_t \left[\frac{S_i - S_e}{xt} - \frac{K_L \, (S_e - S_a)}{x}\right] = \frac{\mu_{max} \, S_e}{K_s + S_e}$$

$$\frac{1}{Y_t \left[\frac{S_i - S_e}{Xt} - \frac{K_L(S_e - S_a)}{X}\right]} = \frac{1}{S_e} \, \frac{K_s}{\mu_{max}} + \frac{1}{\mu_{max}}$$

Kincannon and Stover

$$\left(\frac{dS}{dt}\right)_G = \left(\frac{U_{max}\ FS_{i/XV}}{K_B + FS_{i/XV}}\right) X$$

$$0 = FS_i - FS_e - \frac{\left(U_{max}\ FS_{i/XV}\right)\ XV}{K_B + FS_{i/XV}} - K_L\ (S_e - S_a)\ V$$

$$\frac{S_i - S_e}{Xt} - \frac{K_L\ (S_e - S_a)}{X} = \frac{U_{max}\ FS_{i/XV}}{K_B + FS_{i/XV}}$$

$$\frac{1}{\frac{S_i - S_e}{Xt} - K_L\ \frac{(S_e - S_a)}{X}} = \frac{1}{FS_{i/XV}}\ \frac{K_B}{U_{max}} + \frac{1}{U_{max}}$$

In addition, if a solids mass balance is made:

$$\left(\frac{dX}{dt}\right)_R V = Y_t(S_i - S_e)\ F - k_d XV - Y_t K_L (S_e - S_a) V - (F - F_w) X_e - F_w X_R$$

where

$$\left(\frac{dX}{dt}\right)_R = 0$$

dividing by the volume and solving

$$\frac{(F - F_w)\ X_e + F_w X_R}{VX} = \frac{Y_t\ (S_i - S_e)}{Xt} - kd - \frac{Y_t\ K_L\ (S_e - S_a)}{X}$$

and

$$\frac{(F - F_w)\ X_e + F_w\ X_R}{VX} = \mu_n$$

then

$$\mu_n = Y_t\ \left[\frac{S_i - S_e}{xt} - \frac{K_L\ (S_e - S_a)}{X}\right] - k_d$$

It is seen that the correction for all biokinetic constants involves subtracting the stripping term, K_L (Se - S_a)/X, from the specific substract utilization rate (Si - S_e)/Xt.

The stripping constant K_L was determined from the nonbiological stripping studies. These values are presented in Table 55. Stripping constants were not determined for 1,2 dichlorobenzene and 1,3 dichlorobenzene because it appeared that chemical oxidation also occurred in these units. This made the determination of stripping difficult.

Utilizing the stripping constants given in Table 55 and the developed equations the biokinetic constants were corrected to account for stripping. No correction was needed for BOD_5 constants. The corrections for TOC are given in Tables 56 and 57 and the corrections for COD are given in Tables 58 and 59. Since no corrections were needed for BOD_5, it can be reasoned that stripping had no effect on the ability to predict biokinetic constants for combined chemical systems from single chemical systems. It was also found that, even though stripping did make a difference for a few of the TOC and COD biokinetics, it did not greatly improve the ability to predict these constants. It appears that predicting biokinetic constants for combined chemical systems from single chemical systems is very complex and difficult to accomplish with a high degree of reliability.

TABLE 55. STRIPPING CONSTANTS (K_L) FOR CHEMICALS STUDIED

Chemical	K_L, days^{-1}
Acrylonitrile	9.1
Phenol	0
2,4-Dinitrophenol	0
2,4-Dichlorophenol	0
Pentachlorophenol	0
1,2-Dichlorobenzene	-
1,3-Dichlorobenzene	-
Nitrobenzene	2.3
Benzene	448.9
Toluene	820.0
Ethylbenzene	800.0
Methylene Chloride	747.2
1,2-Dichloroethane	265.7
1,1,1-Trichloroethane	293.9
1,1,2,2-Tetrachloroethane	55.4
1,2-Dichloropropane	455.0
Trichloroethylene	658.1
Chloroform	578.8
Carbon Tetrachloride	503.9
Acrolein	4.8
Phenanthrene	12.3
Naphthalene	13.2
Bis (2-Ethylhexyl) Phthalate	0
Ethyl Acetate	6.05

TABLE 56. CORRECTED BIOKINETIC CONSTANTS FOR SINGLE CHEMICAL SYSTEMS (TOC)

Compound	k_d days^{-1}	Y_t mg/mg	K_e' days^{-1}	μ_m days^{-1}	K days^{-1}	K_s mg/ℓ
Benzene	NC	NC	NC	NC	NC	NC
Toluene	NC	NC	NC	NC	NC	NC
Ethylbenzene	NC	NC	NC	NC	NC	NC
Methylene Chloride	NC	NC	NC	NC	NC	NC
1,2-Dichloroethane	NC	1.39	2.5	NC	2.9	NC
1,1,1-Trichloroethane	NC	0.85	4.9	NC	4.6	NC
1,1,2,2-Tetrachloroethane	NC	0.77	12.5	NC	5.2	NC
1,2-Dichloropropane	NC	1.03	3.6	NC	2.8	NC
Trichloroethylene	NC	1.03	5.6	NC	1.9	NC
Chloroform	NC	NC	NC	NC	NC	NC
Carbon Tetrachloride	NC	NC	NC	NC	NC	NC
Ethyl Acetate	NC	NC	NC	NC	NC	NC

NC - No correction needed

50 percentile constants

TABLE 57. CORRECTED BIOKINETIC CONSTANTS FOR COMBINED CHEMICAL SYSTEMS (TOC)

Combined Systems	k_d days^{-1}	Y_t days^{-1}	K_e' mg/mg	μ_m days^{-1}	K days^{-1}	K_s mg/ℓ
I	NC	NC	NC	NC	NC	NC
II	NC	1.06	4.0	NC	3.5	NC
III	NC	NC	NC	NC	NC	NC
IV	NC	1.18	2.5	NC	1.9	NC
V	NC	NC	NC	NC	NC	NC
VI	NC	NC	NC	NC	NC	NC
VII	NC	NC	NC	NC	NC	NC
VIII	NC	NC	NC	NC	NC	NC

NC - No correction needed

50 percentile constants

TABLE 58. CORRECTED BIOKINETIC CONSTANTS FOR SINGLE CHEMICAL SYSTEMS (COD)

Compound	k_d days-1	Y_t mg/mg	K_e' days-1	μ_m days-1	K days-1	K_s mg/ℓ
Benzene	NC	NC	NC	NC	NC	NC
Toluene	NC	NC	NC	NC	NC	NC
Ethylbenzene	NC	NC	NC	NC	NC	NC
Methylene Chloride	NC	NC	NC	NC	NC	NC
1,2-Dichloroethane	NC	0.53	4.3	NC	3.9	NC
1,1,1-Trichloroethane	NC	0.28	19.2	NC	9.3	NC
1,1,2,2-Tetrachloroethane	NC	0.30	21.2	NC	7.7	NC
1,2-Dichloropropane	NC	0.54	5.0	NC	1.8	NC
Trichloroethylene	NC	0.39	28.0	NC	3.8	NC
Chloroform	NC	NC	NC	NC	NC	NC
Carbon Tetrachloride	NC	NC	NC	NC	NC	NC
Ethyl Acetate	NC	NC	NC	NC	NC	NC

NC - No correction needed

50 percentile constants

TABLE 59. CORRECTED BIOKINETIC CONSTANTS FOR COMBINED CHEMICAL SYSTEMS (COD)

Combined Systems	k_d days^{-1}	Y_t mg/mg	K_e' days^{-1}	μ_m days^{-1}	K days^{-1}	K_s mg/ℓ
I	NC	NC	NC	NC	NC	NC
II	NC	0.57	11.0	NC	4.7	NC
III	NC	NC	NC	NC	NC	NC
IV	NC	0.85	10.9	NC	1.8	NC
V	NC	NC	NC	NC	NC	NC
VI	NC	NC	NC	NC	NC	NC
VII	NC	NC	NC	NC	NC	NC
VIII	NC	NC	NC	NC	NC	NC

NC - No correction needed

50 percentile constants

Effluent Priority Pollutant Concentrations

It is not only important to be able to predict the required aeration tank volume of an activated sludge process, but it is also important to be able to predict the effluent priority pollutant concentrations. To be able to accomplish this, one must also be able to predict the fate of each priority pollutant. The effluents achieved for the specific priority pollutants in the single chemical systems are shown in Table 60. The effluent concentrations are shown based upon the removal mechanism. These being biodegradation, complete stripping, and stripping plus biodegradation. The Henry's Law Constant, log partition coefficient, and percent biodegraded during static tests are also given. Based upon these results, it can be predicted that nitrogen compounds, phenols, oxygenated compounds, polynuclear aromatics, and phthalates will be removed by biological degradation. Aromatics will be removed by both biological degradation and stripping, except when the Henry's Law Constant is in the 10^{-5} atm.m^3/mole range, then that chemical will be removed by biological degradation only. Halogenated hydrocarbons present a special problem. Some are removed by stripping, whereas others are removed by combined biodegradation and stripping. No parameter, such as Henry's Law Constant or partition coefficient was found that would predict which removal mechanism would persist. Therefore, biodegradability studies could be used to predict which halogenated hydrocarbons would be removed by both stripping and biodegradation.

In order to predict the concentration of each priority pollutant in an effluent, biokinetic constants based upon the priority pollutant must be determined. This was done using Eckenfelder's second order model and Kincannon and Stover's design model. Lawrence and McCarty and Gaudy's models were not used because their models require either Y_t or μ_{max} and growth based upon only the priority pollutant was not available. Growth in the systems were due to utilization of the "base mix" and the priority pollutant. Thus, data was not available for determining the Lawrence and McCarty and Gaudy's biokinetics in terms of the specific chemical. The biokinetic constants for Eckenfelder's model (K_e') and Kincannon and Stover's model (U_{max}, K_B) could be determined. The stripping and biokinetic constants are given in Table 61. If the mass balances which include stripping are solved for S_e we obtain.

Eckenfelder

$$S_e = \frac{S_i + K_L\, S_a\, t}{1 + \dfrac{K_e'\, Xt}{S_i} + K_L\, t}$$

Kincannon and Stover

$$S_e = \frac{S_i - \dfrac{U_{max}\, S_i}{K_B + FS_{i/XV}} + K_L\, S_a\, t}{1 + K_L\, t}$$

TABLE 60. EFFLUENT ACHIEVED FOR SPECIFIC TOXIC ORGANICS

Compound	Henry's Law Constant atm.m^3/mole	Log Pow	Percent Biodegradable	Influent mg/ℓ	Effluent Achieved μg/ℓ Biological	Stripping plus biodegradation	Complete Stripping
Nitrogen Compounds							
Acryloniteile	6.3×10^{-5}	-0.14	100	152	≤50		
Phenols							
Phenol	1.3×10^{-6}	1.46	97	173	<10		
2,4 dinitrophenol	* N.A.	7.53	100	96	660		
2,4 dichlorophenol	4.2×10^{-5}	2.75	100	75	3600		
Pentachlorophenol	2.1×10^{-6}	5.01	100	8	170		
Aromatics							
1,2 dichlorobenzene	1.9×10^{-3}	3.38	33	83		<50	
1,3 dichlorobenzene	2.6×10^{-3}	3.38	59	69		340	
Nitrobenzene	2.4×10^{-5}	1.86	94	100	2200		
Benzene	6.0×10^{-3}	2.04	43	153		40	
Toluene	5.9×10^{-3}	2.69	100	59		≤10	
Ethylbenzene	5.8×10^{-3}	3.15	85	60		80	
Halogenated Hydrocarbons							
Methylene chloride	3.2×10^{-3}	1.25	100	180		510	
1,2 dichloroethane	1.1×10^{-3}	1.48	23	258			3700
1,1,1 trichloroethane	4.9×10^{-3}	2.17	25	118			1600
1,1,2, 2 tetrachloroethane	4.2×10^{-4}	2.56	27	201			11000
1,2 dichloropropane	2.8×10^{-3}	2.28	39	182			1800
Trichloroethylene	1.2×10^{-3}	2.27	80	95		210	
Chloroform	3.4×10^{-3}	1.97	85	35		200	
Carbon tetrachloride	3.0×10^{-2}	2.69	100	19		130	
Oxygenated Compounds							
Acrolein	9.7×10^{-5}	-0.09		62	≤50		
Polynuclear Aromatics							
Phenanthrene	1.3×10^{-4}	4.46	100	0.56	<10		
Naphthalene	1.2×10^{-3}	3.37	100	6.9	≤10		
Phthalates							
Bis 2 Ethylhexyl	N.A.	8.73	0	0.26	60		
Other							
Ethyl acetate	N.A.	N.A.		1.67	60		

* Not Available

Using these equations and the constants given in Table 61, the effluent concentrations of the specific priority pollutants in the combined units were predicted. The stripping rate constants were determined from the nonbiological systems. The biological removal rate constants were determined by correcting the substrate utilization rate by accounting for stripping. The constants were determined by using mean values. Since the Kincannon and Stover model was not planned for when developing the work plan, the data collected was not ideal for determining U_{max} and K_B.

When predicting S_e with stripping as one removal mechanism the estimation of S_a becomes a problem for closed systems as the experimental unit was. In an open system the concentration of the chemical in the air space above the reactor can be assumed to be zero. In a closed system this will not be the case. However, it also becomes difficult if not impossible to estimate S_a for a closed system. For the purpose of these predictions, S_a was assumed to be zero. The predicted concentrations are given in Table 62. It is seen that both Eckenfelder's model and Kincannon and Stover's model predicted the effluent concentrations very well. In fact, both models made very similar predictions.

While making the calculations for these predictions an important observation was made. When S_a was assumed to be zero for the halogenated hydrocarbons, stripping became the dominate removal mechanism for all halogenated hydrocarbons studied. Apparently under closed system conditions methylene chloride, trichloroethylene, chloroform, and carbon tetrachloride were held in solution a sufficient period of time so that biological degradation took place. However, according to the calculations, an open system would allow these chemicals to strip at such a rate that biological degradation would not occur. It appears that additional work needs to be conducted in regards to stripping of priority pollutants.

DISCUSSION OF RESULTS

Treatment efficiencies when measured in terms of BOD_5, TOC, and COD were very high for all systems in this study. The mean BOD_5 did not exceed 10.0 mg/ℓ for any system. Generally, the mean BOD_5 was below 5.0 mg/ℓ. This indicates that the "base mix" was highly biodegradable. This factor did create problems in obtaining data for determining biokinetic constants. The ideal situation is one in which the effluent BOD_5 varies over a wide range. However, with the wastewaters used in this study, even an SRT of 2 days produced a very low effluent BOD_5. Therefore, SRT values of 2,4, and 6 days produced effluent BOD_5's with very little difference. The high treatment efficiencies also indicates that the priority pollutants used in this study had very little or no effect on the biological treatment of the wastewater. Even when the priority pollutant was not biodegraded, it did not affect the treatment efficiency.

The biokinetic constants obtained for the control unit are within a range that would represent a readily biodegradable wastewater. It is interesting to compare K_e' for the various units. Tetrachloroethane, nitrobenzene,

TABLE 61. STRIPPING AND BIOLOGICAL REMOVAL RATES FOR SPECIFIC COMPOUNDS FROM SINGLE SYSTEMS

Compound	K_L days^{-1}	K_e' days^{-1}	U_{max} mg/mg·day	K_B mg/mg·day
Biodegradation				
Acrylonitrile	9.1	x	x	x
Phenol	0	x	x	x
2,4 Dinitrophenol	0	24.0	20.0	20.1
2,4 Dichlorophenol	0	2.3	0.7	0.7
Pentachlorophenol	0	0.8	0.6	0.6
Nitrobenzene	2.3	5.2	1.0	1.0
Acrolein	4.8	1.9	x	x
Phenanthrene	12.3	x	x	x
Naphthalene	-	0.35	0.5	0.5
Bis (2 ethylhexyl) phthalate	13.2	0.002	0.001	0.001
Biodegradation Plus Stripping				
1,2 Dichlorobenzene	--	--	--	--
1,3 Dichlorobenzene	--	--	--	--
Benzene	448.9	60.0	25.0	25.0
Toluene	820.0	33.6	19.9	19.9
Ethyl benzene	800.0	4.6	10.0	10.0
Methylene chloride	747.2	5.0	14.7	14.7
Trichloroethylene	658.1	0.7	5.3	5.3
Chloroform	578.8	0.2	21.1	21.1
Carbon tetrachloride	503.9	0.1	20.0	20.0
Ethyl acetate	6.1	16.5	13.2	13.2
Stripping				
1,1,2,2 Tetrachloroethane	55.4	--	--	--
1,2 Dichloropropane	455.0	--	--	--
1,1,1 Trichloroethane	293.9	--	--	--
1,2 Dichloroethane	265.7	--	--	--

x - Effluent at detection level

TABLE 62. PREDICTED EFFLUENT SPECIFIC COMPOUND LEVEL IN COMBINED SYSTEMS

Compound	Influent mg/ℓ	Predicted Effluent µg/ℓ Modified Eckenfelder	Predicted Effluent µg/ℓ Kincannon Stover	Measured Effluent µg/ℓ
Nitrogen compounds				
Acrylonitrile	31.0	≤50	≤50	30
Phenols				
Phenol	65.0	<10	<10	<10
2,4 Dinitrophenol	32.0	180	270	250
2,4 Dichlorophenol	24.1	710	2500	5500
Pentachlorophenol	3.7	60	75	83
Aromatics				
1,2 Dichlorobenzene	10.0	≤50	≤50	50
1,3 Dichlorobenzene	20.0	--	--	25
Nitrobenzene	37.5	1000	2500	24800
Benzene	39.0	50	≤10	≤50
Toluene	16.8	15	≤10	≤10
Ethylbenzene	19.3	65	≤10	≤10
Halogenated Hydrocarbons				
Methylene chloride	56.0	190	≤10	50
1,2 Dichloroethane	63.0	710	710	1100
1,1,1 Trichloroethane	60.0	610	610	94
1,1,2,2 Tetrachloroethane	52.0	2700	2700	2000
1,2 Dichloropropane	48.0	320	320	170
Trichloroethylene	65.5	290	15	100
Chloroform	14.0	70	≤10	105
Carbon tetrachloride	7.0	40	≤10	7
Oxygenated Compounds				
Acrolein	31	≤50	≤50	30
Polynuclear Aromatics				
Phenanthrene	0.56	≤10	≤10	≤10
Naphthalene	2.3	40	25	≤50
Phthalates				
Bis (2 ethylhexyl)	0.35	110	30	≤50
Other				
Ethyl acetate	63.0	700	200	50

2,4 dichlorophenol, 1,2-dichlorobenzene, 1,3 dichlorobenzene, 1,1,1-trichloroethane, pentachlorophenol, trichloroethylene and chloroform had K_e' values close to the control. Acrylonitrile, acrolein, 2,4-dinitrophenol, carbon tetrachloride, and naphthalene had K_e' values lower than the control. 1,2 dichloropropane, benzene, methylene chloride, ethyl acetate, phenol, 1,2-dichloroethane, bis (2-ethylhexyl) phthalate, toluene, ethylbenzene and phenanthrene had K_e' values greater than the control. The lowest K_e' observed occurred with acrolein, the 50 percentile value being 29 days^{-1}. This still represents a highly biodegraded wastewater. The other biokinetic constants followed the same pattern as K_e'.

The normal approach for analyzing and presenting biological system data is to plot the average values at each μ_n or SRT. This approach masks the actual scatter of the data and provides an average value or 50 percent probable value for the biokinetic constants to be used in design. Use of these biokinetic constants will provide a system capable of achieving the desired effluent quality only 50 percent of the time. The allowed statistical variability of the effluent discharge criteria must be evaluated to determine the appropriate biokinetic constants to use for design. Designing to meet a specific effluent quality 95 percent of the time will require a significantly larger reactor volume than that required for 50 percent of the time and will require use of the 95 percent probable biokinetic constants, as shown in the following example.

Using Eckenfelder's design model and the following design conditions the impacts of data variability for the acrylonitrile containing wastewater can be demonstrated.

F = 10 MGD
S_i = 200 mg/ℓ BOD_5
S_e = 5 mg/ℓ BOD_5
X = 1000 mg/ℓ volatile suspended solids

The activated sludge reactor volumes are determined as follows:

$$V = \frac{FS_i(S_i - S_e)}{X K_e' S_e}$$

Using the 50 percent line or $K_e' = 31$, the required reactor volume will be:

$$V = \frac{10 \times 10^6 \times 200 \times (200-5)}{1000 \times 31 \times 5}$$

$$V = 2{,}516{,}000 \text{ gallons}$$

This reactor volume of 2,516,000 gallons should provide an effluent soluble BOD_5 (S_e) of 5 mg/ℓ 50 percent of the time. Using the 95 percent line or $K_e' = 11$, the required reactor volume will be:

$$V = \frac{10 \times 10^6 \times 200\ (200-5)}{1000 \times 11 \times 5}$$

$$V = 7{,}091{,}000 \text{ gallons}$$

This reactor volume of 7,091,000 gallons is almost three times the previous reactor volume and should provide an effluent soluble BOD_5 (S_e) of 5 mg/ℓ 95 percent of the time. Using the 75 percent line or $K_e' = 19$, the required reactor volume will be 4,105,000 gallons. If the reactor volume was designed at 2,516,000 gallons the following probability of occurrence of S_e could be expected:

Probability Level	S_e
50%	5 mg/ℓ
75%	8 mg/ℓ
95%	14 mg/ℓ

The variability analysis approach presented indicated that K_d was a true biokinetic constant. μ_{max} was also treated as a true biokinetic constant, and since $\mu_{max} = K \cdot Y_t$, and Y_t was found to be a variable biokinetic coefficient, μ_{max} and K could not both be treated as constants. If $Y_t = \mu_{max}/K$ varies, μ_{max}, K, or both must vary. If both μ_{max} and K vary, the prediction of these coefficients becomes more difficult. The decision to make μ_{max} a biokinetic constant and K a variable biokinetic coefficient depending on the variable biokinetic coefficient Y_t simplifies the prediction of μ_{max} and K. The following reasoning was used in the selection of μ_{max} as a biokinetic constant.

K is simply the maximum U, and U was found to vary at constant μ_n or μ. At μ_{max}, U would be equal to K and could be expected to be variable. Also in a heterogeneous population such as in the activated sludge process treating a particular wastewater, several different kinds of bacteria will actually be in predominance; however, shifts in the ratios of these specific microorganisms in predominance can change. As these population dynamic shifts occur Y_t changes, and thus the mixed liquor solids (X) changes. The specific substrate utilization rate (U), could be expected to change as X changes; however, μ_{max} should not change. As μ_n or μ approaches μ_{max} the microorganisms with lower μ_{max} values than the existing μ_n or μ will be washed out of the system. Therefore, the microorganisms with the greatest μ_{max} will predominate at the μ_{max} condition of the system. At this absolute μ_{max} which could be considered to be a constant, many microorganisms will have been washed out of the system, but several microorganisms will still remain. These few organisms may still provide a variable maximum U or K value but with lower variability since the few remaining organisms should provide less variability. All the other substrate utilization terms (K_s and K_e' or K_e) were also found to be variable in a manner similar to the true yield. Even at very constant controlled μ_n's or SRT's all the substrate utilization characteristic descriptors were found to be variable. Based on this reasoning, Y_t, K_e', K_e, K_s and K are all considered to be variable biokinetic coefficients, while K_d and μ_{max} are considered to be biokinetic constants. The variability observed in these biokinetic coefficients during the treatability study can and should be considered during scale-up design to achieve specific effluent discharge criteria.

In addition to the variability analysis for the existing models, a new model has been presented. This model provides an approach in which there is no variability of the biokinetic constants. All variability can be handled as influent variability and normal procedures can be used. The new design model provides design values comparable with the other design models.

This study has also looked at the possibility of predicting the fate and effluent concentrations of the various priority pollutants. It has been found that good predictions for the priority pollutants can be made. In general, it can be predicted that nitrogen compounds, phenols, oxygenated compounds, polynuclear aromatics, and phthalates will be removed by biological degradation. Aromatics will be removed by both biological degradation and stripping, except when the Henry's Law Constant is in the 10^{-5} atm.m^3/mole range then that chemical will be removed by biological degradation only. Halogenated hydrocarbons present a special problem. Some are removed by stripping, whereas others are removed by combined biodegradation and stripping. No parameter, such as Henry's Law Constant or partition coefficient was found that would predict which removal mechanisms would persist. It was also found that the type of reactor could be a factor. Therefore, biodegradability studies must be conducted. If the biodegradability is high, the chemical will be both stripped and biodegraded.

It was also found that biodegradability and stripping constants could be developed for each priority pollutant and used very successfully in predicting the effluent concentrations for the pollutants when combined with other priority pollutants or when the influent concentrations varied.